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ABSTRACT

Air Force support of a Center of Excellence at Stanford University has provided the impetus and core for a major new entity, the Center for Automation and Manufacturing Science (CAMS). The new center draws from two well-known research groups at Stanford: the Robotics Group of Stanford's Artificial Intelligence Laboratory and the Automatic Control Group of Stanford's Department of Aeronautics and Astronautics. Ten professors and some 50 graduate students are participating in CAMS activities. CAMS in turn is the first of a new complex of centers at Stanford involved in the manufacturing enterprise: the Stanford Institute for Manufacturing and Automation (SIMA). Strong industrial interaction is a primary objective of SIMA.

In our Air Force program we are focusing on robotic aspects of automation. Our goal is to make fundamental contributions to the underlying set of technologies that will enable the next generation of industrial robots to be far more capable than today's — will enable them to be lightweight, limber, deft, facile, quick, friendly, low-powered, seeing, sensing, thinking machines that can reason and strategize — can carry out tasks assigned at a high conceptual level.

Specifically, our research focus is on fast, precise control of lightweight (flexible) manipulators, sensing, especially optical and tactile sensing, intelligent systems for robot task management, and computer vision for robot management.

We are addressing the question of how to provide manipulator control so good that a whole new generation of manipulators can be developed — manipulators that are much lighter and far more facile than anything today's control systems could stably manage. To do this we have begun to develop a sequential family of new manipulators that are extremely light and flexible, deliberately exaggerating the control problem so that it will have to be solved in much more fundamental ways than it ever has before.

The central control problem for each of these manipulator systems is the problem of controlling the end-point (fingertips) of a manipulator by measuring position or force ***at that point*** and using ***that*** measurement to control torque at an actuator at the other end (elbow or shoulder) of the flexible manipulator. This turns out to be, for fundamental stability reason, ***very hard to do***.

For very flexible manipulator arms (two-second vibration period), we have succeeded in achieving control that is not only stable but highly robust, and at a speed limited basically by wave propagation times in the manipulators themselves.

We have also developed control for a small, quick-acting wrist mounted on the end of the flexible arm. A lamp is mounted at the tip of the wrist. A silicon photo sensor mounted above senses the position of the lamp, and this tip position is the primary signal for controlling the tip. The long flexible arm moves the wrist from one work station to the next. Then a commanded change in tip position within the work station is accomplished by the fast wrist almost instantaneously, and that tip position is held rigidly in space while the slower flexible-arm end is brought into alignment. (It is striking to watch the tip obey commands in space so precisely, regardless of motion of its supporting links.) In future we will be able to add touch sensing, perform snatch-and-place, add a second short link, and learn new techniques to use on our large two-link arm control development.

This year we have also completed construction of another major facility, a two-link experimental arm driven by very flexible tendons. Such a flexible drive train — tendon or gear train — is a very common charactristic of commercial robots. We have identified the system's dynamic characteristics by open-loop tests and have accomplished closed-loop control using sensors colocated with the drive motors, which is easy. During the coming years we plan to develop fast, stable, precise control of the two-link arm using end-point sensing, which will be very hard. We have also developed a strategy for chasing and quickly capturing a moving target, such as a swinging part to be assembled.

We are developing a sensor for perceiving, by touch, the shape or texture of objects. Spatial information is to be generated by an array of capacitive pressure sensors, data from which are to multiplexed together for transmission to a remote site.

During this first year, effort has focused on the development of the required integrated sensors and circuits. A capacitor was chosen as the transduction element due to its superior sensitivity over piezoresistive pressure sensors. Special micromachining techniques for forming this structure include chemical etching, laser drilling and welding, micro-sandblasting, and electrostatic bonding. During the past year, an automated laser workstation for micromachining glass wafers has been developed and used to produce arrays of electrical

vias. A set of photomasks for a Mechanical Test Chip (MTCHIP) has been laid out. A RATFOR program has been written to control the workstation. Patterns of holes in 300 micron thick pyrex wafers have been produced.

A Mechanical Test Chip has been designed and laid out to test etching techniques for the pressure sensitive silicon diaphragm.

Signal processing and output format required for the integrated capacitive pressure sensor has been designed. This circuit has been designed, simulated, breadboarded, laid out, fabricated, and tested.

Assembly of an electric motor was performed using the IBM RS-1 robot.

A system of real-time collision avoidance was implemented. The system is based on the use of potential functions around obstacles. Obstacles are described by composition of primitives which are approximately cylinders and blocks. The method requires a small amount of calculation; it allows obstacle avoidance to occur in real time as an integral part of the servo-control. An experimental manipulator programming system "COSMOS" using the method has been designed for the PUMA and demonstrated with obstacles (including mobile obstacles) detected by an MIC vision module. So far, the simulator has been used to test three adaptive control schemes, several dynamic control schemes, and two parameter estimation schemes.

A new, nonlinear, and generalizable technique has been developed that will continually monitor the parameters of a robot arm to estimate continuously the inertial forces and the friction in robot joints. This system has also been simulated for a three link robot, and has been successfully applied to a physical single link robot as well.

We have completed joint force sensing for one joint of the PUMA, and have designed a touch sensing finger which senses three components of force.

Research in vision has a focus on intelligent systems which support not only inspection and vision but the total robotics and manufacturing research program. Contributions have been made toward a successor for ACRONYM, an intelligent system developed at Stanford and adopted by about a dozen laboratories and companies. The modeling system of SUCCESSOR is greatly generalized to include multiple naming, holes and set operations on volumes (union, intersection, difference). Work in other areas of computer vision, includes architecture of VLSI vision processors, segmentation with edge operators, graphics support, and hardware support.

Implementation of a new edge operator, tests of shape from a shading algorithm, and experimentation toward building an active ranging device are under way.

Both software and hardware support for vision systems include: software for interfacing the Grinnell display; LISP graphics; interface for an inexpensive TV input system; convolution software; TV time base corrector; an interface for an Optronics drum scanner; work on software for a GTCO digitizing tablet; and an interface for an image hardcopy output device.

The new Center for Automation and Manufacturing Science at Stanford has drawn us together in many ways during this first year, and has begun to attract a number of our talented colleagues to contribute in important ways to manufacturing technology. We have had a steady stream of visitors to our Center from many industries and from the world scientific community in robotics. We have taken part in several key invitational conferences with governmental research leaders in the field. And we have begun several new joint projects with industrial partners.

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EXECUTIVE SUMMARY

Introduction

The Air Force Office of Scientific Research has established, with major three-year funding, a Center of Excellence at Stanford University to develop new technologies that will be key to advancing automation of manufacturing processes, with specific Air Force concern for assembly, test, and rework. These areas represent important economic leverage in the affordability of Air Force systems.

The new Center draws from two internationally known research groups at Stanford: the Robotics Group of Stanford's Artificial Intelligence Laboratory, and the Automatic Control Group of Stanford's Department of Aeronautics and Astronautics. A common objective that we are able to address together, with this major Air Force support, is to advance the effectiveness of automation in manufacturing by mounting research concurrently — and synergistically — into a set of the primary, pacing technologies in automation, as we outline below.

Our Center—the Center for Automation and Manufacturing Science (CAMS)—is the first of a new complex of centers at Stanford involved in the manufacturing enterprise: the Stanford Institute for Manufacturing and Automation (SIMA). The other founding Centers are CTRIMS, for graduate education in manufacturing operations, and the Center for Design Research (CDR) which will pursue creative use of the computer aided prototyping process. We expect the addition of other centers to SIMA—in metal formability, for example. We will also interact in many ways with existing centers at Stanford, such as the Center for Materials Research and the large Center for Integrated Systems of which Professor Meindl (a principal investigator on this AFOSR Center of Excellence program) is Codirector. The interrelation between the Centers of SIMA is shown in Fig. 1-1 where particular faculty are listed, along with sources of funding.

Within CAMS we are addressing a number of automation issues. For example, a major project for automation of ultra-high-precision machining is now underway.

In our Air Force program we have decided to focus on robotic aspects of automation. With their requirements for great flexibility of use and rapid task redirection, the robotic aspect of automated manufacturing will draw upon more of the new technologies, and more deeply, than any other aspect.

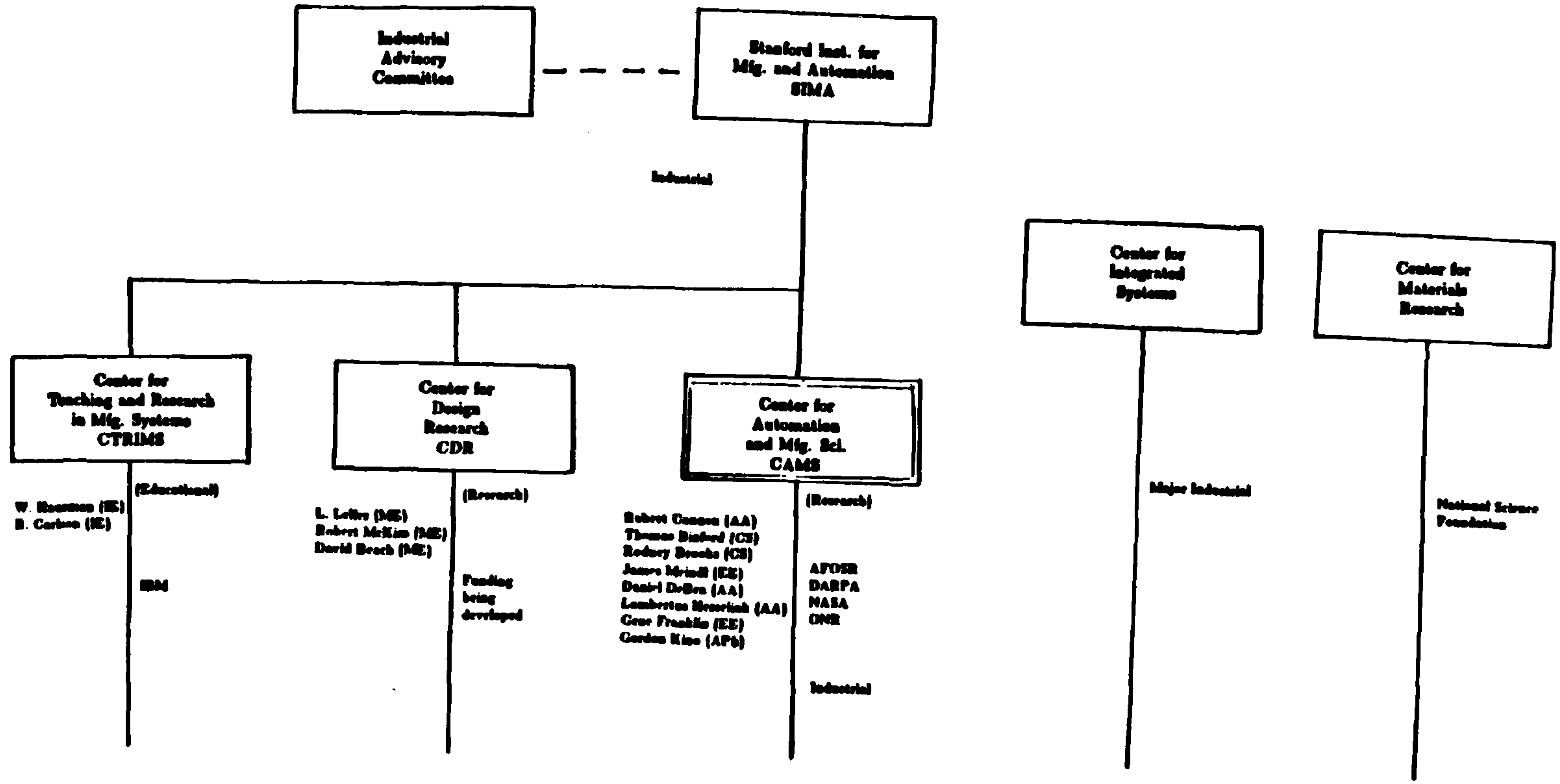
If the right *set of technologies* is developed, we believe the next generation of robots can (by comparison with today's) be lightweight, limber, deft, facile, quick, friendly, low-powered, seeing, sensing, thinking machines. Above all, they will be capable of reasoning and strategizing—of carrying out tasks assigned at a high conceptual level, by "thinking through" the best way to carry out any given task. Robotic devices with such characteristics and capability can provide the flexible automation that will be so important in achieveing higher levels of productivity.

What are the underlying technologies that will be needed as the base for robots with such capabilities? They can be described in four catagories: manipulator control, sensing, thinking, vision. Among us, in our Center, we are working to make useful contributions in all four technical areas. There is, of course, much interaction between, and synergism among the four areas; and that is the exciting thing about the level of effort that the AFOSR program makes possible. Specifically, fast, precise manipulator control is the primary focus of Task 3 of the program, tactile sensing of Task 4, and computer-based thinking and vision of Task 2. But these depend upon each other altogether as diagramed in Fig. 1-2, and draw upon one another in many ways. We feed back signals from many sensors—optical and eventually perhaps acoustic, as well as tactile and force—to effect good end-point control of manipulators. New, more competent manipulators, with their multiple sensors, will be utilized avidly by task-management systems to produce new assembly sequences that are quicker, more precise, and more efficient.

More acute robot vision, together with more-rapid visual *perception* (scene analysis), are very important basics for more effective task planning, and may even someday be used in real time by the fast manipulator controllers themselves.

And of course in a ubiquitous way our overview task, Task 1, of the program will draw totally upon — and stimulate — all of the other tasks. For Task 1 is to work with the industrial automation community to survey in a continuing way the problems of automation, and to effect technology transfer to designers of new automation systems as each advance becomes demonstrable in our laboratories. Thus while, for

Fig. 1-1. Cooperation of Air Force Center of Excellence (CAMS) with Other Stanford Centers.



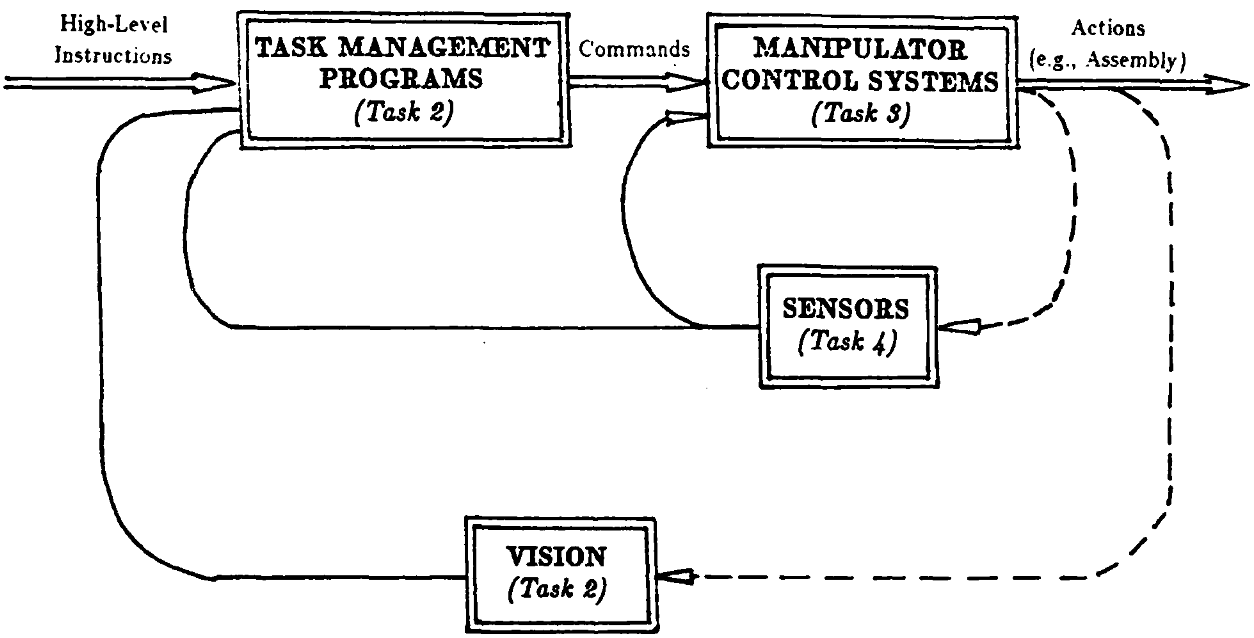
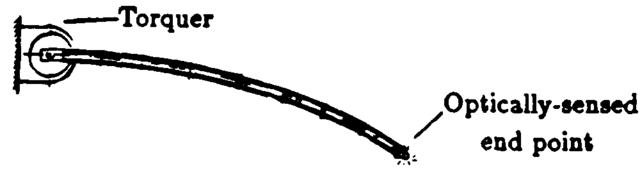


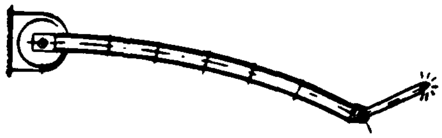
Figure 1-2. The Anatomy of a High-Level Robot

(a) Very flexible one-link manipulator
(Rapid pick and place)

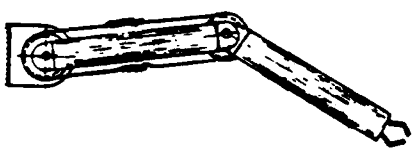


(b) Very flexible manipulator with force control
(Slew and touch moving target)

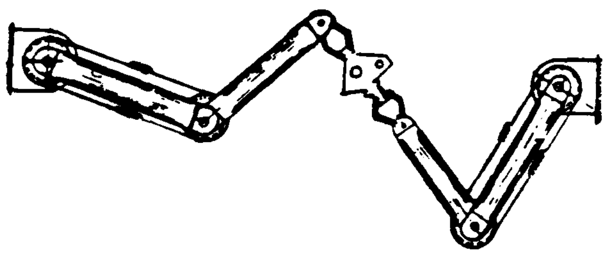
(c) Flexible manipulator with fast wrist
(Precise snatch and place)



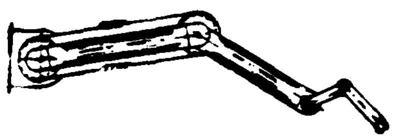
(d) Two-link Arm with Elastic Tendons
(2D pick and place)



(e) Cooperating Two-Link Arms
("Long-Part" handling)



(f) Two-Link Arm with Double Wrist
(Very fast, precise 2D tasks)



(g) Two-Flexible-Link Arm

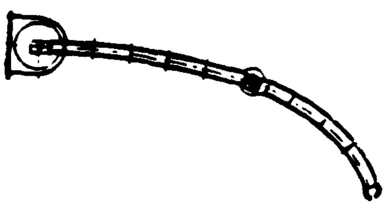


Figure 1-3. The Sequence of Experimental Very Flexible Manipulators.

convenience, we discuss the four research Task areas separately in the following paragraphs, they are in fact highly interrelated in our Center.

Rapid Precise Control of Nonrigid Manipulators

Manipulators — arms and hands with their actuators, and the increasingly sophisticated feedback systems that control their movements — are the "business end" of a robot, where parts are mechanically moved, formed, placed, fitted together (or dismantled), and inspected. In our Controls Group we are addressing the question of how to provide manipulator control so good that a whole new generation of manipulators can be developed— manipulators that are much lighter and far more facile than anything today's control systems could stably manage.

To do this we have begun to develop a sequential family of new manipulators that are extremely light and flexible, deliberately exaggerating the control problem so that it will have to be solved in much more fundamental ways than it ever has before. Some members of our family of manipulators are shown in Fig. 1-3. The family will also of course extend in many ways not shown—to three dimensional action, and to mobile-mounted very flexible manipulator systems, for example.

The central control problem for each of these manipulator systems—and the problem we have been the first to solve—is the problem of controlling the end-point (fingertips) of a manipulator by measuring position or force *at that point* and using *that* measurement to control torque at an actuator at the other end (elbow or shoulder) of the flexible manipulator. This turns out to be, for fundamental stability reasons, *very hard to do*. Every time someone has tried it (this *noncolocated* control) in commercial robots, the robot system has gone unstable.

Using advanced control methods developed in our laboratory we have already succeeded in achieving, for the first three configurations of Fig.1-3, control that is not only stable but highly robust, and at a speed limited basically by wave propagation times in the manipulators themselves. (The achievement for the system in Fig. 1-3(a) was by Eric Schmitz, and for Fig.1-3(b) by James Maples, both under other funding.)

By proceeding step-wise with the sequence of basic manipulator control problems indicated in Fig.1-3, we expect to provide the fundamental new technology for controlling a new generation of lightweight flexible robots.

Fast Wrist on a Flexible Arm

The advance of Fig. 1-3(c), development of a small quick-acting wrist mounted on a very flexible long arm, was accomplished entirely this first year by Wen Wie Chiang explicitly with AFOSR funding. This new system, shown in Fig. 1-4, has several generic implications for future robot systems, which can be inferred from the experimental performance represented in Fig. 1-6.

The wrist, a short link 17 cm. long, is installed at the tip of a 97 cm. flexible beam, Figs. 1-4, and 1-6(a). The wrist is light and rigid compared with the flexible beam, and is controlled by a separate DC motor. A lamp is mounted at the tip of the wrist to indicate the end point position (where various end effectors are to be mounted). A silicon photo sensor mounted above the apparatus senses the position of the lamp, and this tip position is the primary signal for controlling tip position.

Fig. 1-6(b) is a time sequence of the system moving between two work stations. Generically, when a robot manipulator is used in either a fabrication or assembly job, the area of a working station is small compared with the reachable region of the manipulator, a region that may include several stations. To achieve the most efficient operation, the manipulator has to move rapidly from station to station, but at the same time be able to perform tasks within a station under accurate, very-high-bandwidth control.

A rigid and heavy manipulator cannot achieve high speed and bandwidth with a reasonable amount of power consumption. A lighter large manipulator can be moved faster when its flexibility is under proper control, as we have demonstrated (Fig. 1-3(a)); but the maximum bandwidth of the closed loop is still limited by its flexibility, i.e., its wave propagation time. A micro manipulator carried by a larger one can greatly enhance its performance by providing a way to achieve very high bandwidth and precise end point motion within a working station, i.e., within the immediate vicinity of the end of the larger manipulator.

Fig. 1-6 presents an experimental demonstration of how the combination works to get optimum system performance. In Fig. 1-6(b) the long flexible arm moves the wrist from one work station to the next. In Fig.

performance. In Fig. 1-6(b) the long flexible arm moves the wrist from one work station to the next. In Fig. 1-6(c) and (d) a commanded change in tip position within the work station is accomplished by the fast wrist almost instantaneously (A, B), and that tip position is held rigidly in space while the slower flexible-arm end is brought into alignment (C, D, E). (It is striking to watch the tip obey commands in space so precisely, regardless of motion of its supporting links.)

This is our first "two-link" system, and there is much we will be able to accomplish with it: optimizing the small-link-on-large-arm performance, adding touch sensing, performing snatch-and-place, adding a second short link, learning new techniques to use on our large two-link arm control development, and eventually adding a double-small-link system to the large two link arm, Fig. 1-3(f).

Two-Link Arm with Flexible Tendons

The second general area of our research in precise control of flexible manipulators is with the full two-link systems of Figs. 1-3(d) through (g). At this point we have completed construction of the system of Fig. 1-3(d), which is shown in the photograph of Fig. 1-5. (A detailed isometric drawing is given in the Technical Report section, Fig. 3-3.) The arm structures in this system are rigid, but the motors drive them through highly flexible tendons. Such a flexible drive train—tendon or gear train—is a very common characteristic of commerical robots. Subsequent arms will also incorporate flexible structure, Fig. 1-3(g).

Conceptual design of this system is by Michael Hollars, who has identified the system's dynamic characteristics by open-loop tests, and has accomplished closed-loop control using sensors colocated with the drive motors, which is easy. During the coming year he plans to develop fast, stable, precise control of the two-link arm using end-point sensing, which will be very hard.

After that we will begin developing command-following strategies and then target-chase-and-capture strategies, where the target might be a swinging assembly part to be grasped gently (but quickly!), or the end of another robot in a cooperative task, Fig. 1-3(e). A special study of candidate control strategies for the swinging-part problem was completed this year by Bruce Gardner. The results are described in Section 3 of this Technical Report.

Sensors for Robot Systems

New sensors will of course be extremely important components of new, more capable robots. In our early manipulator research we are using simple sensors–e.g., the light-bulb/optical sensor shown in Fig. 2 (a) and (c)–in order to move Task 3 forward in parallel with the development of new sensors. At the same time, in Task 4 of this AFOSR program and in other projects, we are also sponsoring and collaborating with sensor development efforts per se.

The sensor system described under Task 4 of this report is for perceiving, by touch, the shape or texture of objects.

Spatial information is to be generated by an array of capacitive pressure sensors, each as in Fig. 1-7, data from which are to be multiplexed together for transmission to a remote site. Electrically, a bandwidth of 1 - 500 Hz and a response time < 0.1 sec. were stipulated. Mechanically, a touch sensor must provide a spatial resolution of < 2 mm., and must be reliable, easy to repair, and self-protecting.

In developing such a touch sensor, sub-projects include: a) an electromechanical silicon transducer; b) an integrated circuit for signal processing at the site of data collection; c) merger of electromechanical transducer and the on-site processing circuitry into an hermetically packaged integrated silicon sensor; d) an integrated circuit for multiplexing signals from an array of such integrated sensors; and e) incorporation of the integrated array into robotic skin.

During this first year, effort has focussed on the development of the required integrated sensors and circuits.

A capacitor was chosen as the transduction element due to its superior sensitivity over piezoresistive pressure sensors. Special micromachining techniques are needed for forming this structure, including chemical etching, laser drilling and welding, micro-sandblasting, and electrostatic bonding. During the past year, an automated laser workstation for micromachining glass wafers has been developed and used to produce arrays of electrical vias for electrical connection between cables attached to the top of the glass cap and the integrated circuit under the glass cap. In addition, a set of photomasks for a Mechanical Test Chip (MTCHIP) has

Figure 1-4. Very Flexible Manipulator with Quick-Acting Wrist.

Figure 1-5. Experimental Two-Link Arm with Flexible Tendon Drive.

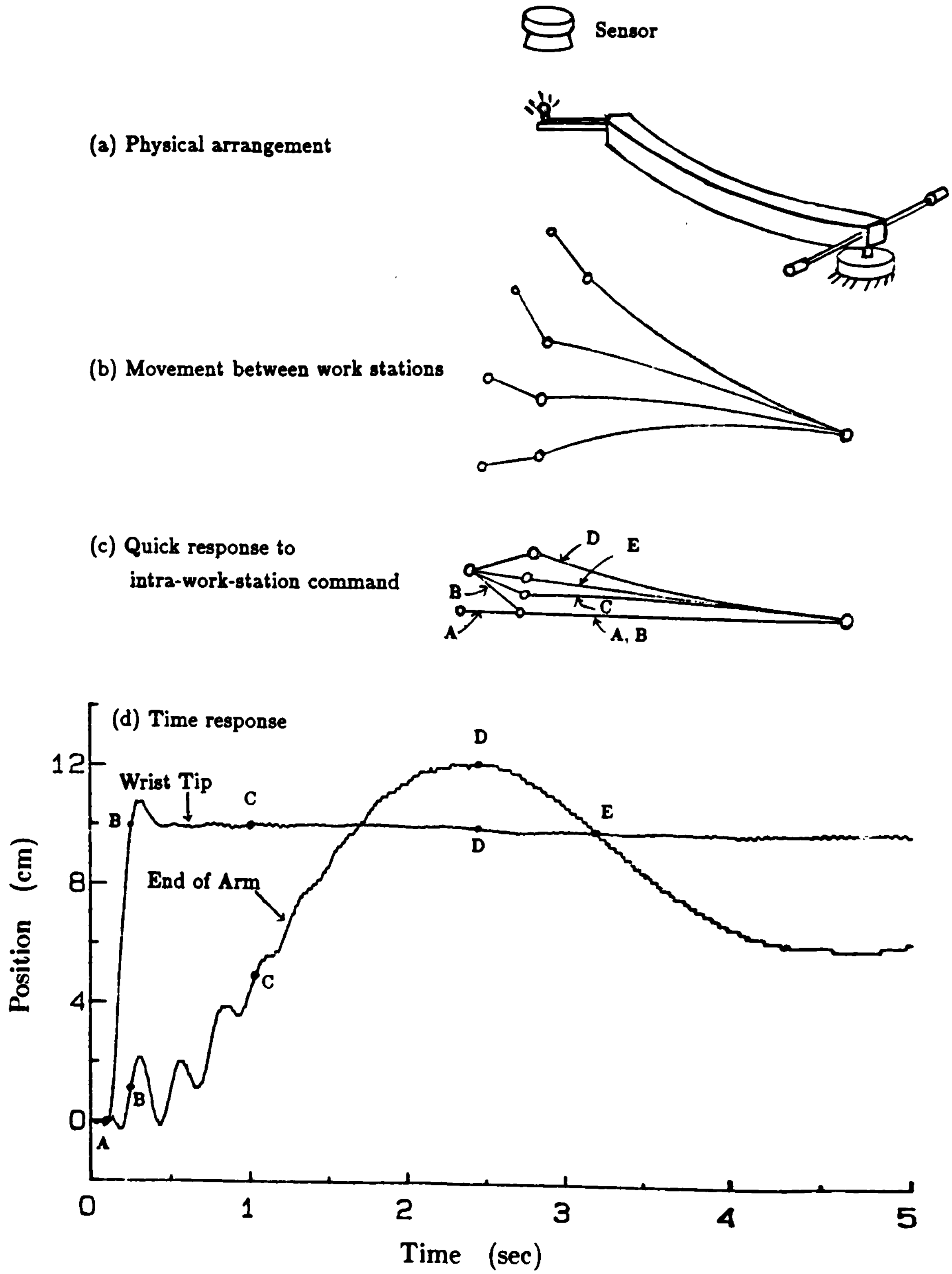


Figure 1-6. Very Flexible Manipulator with Quick-Acting Wrist.

been laid out.

The 5 micron resolution of the XY-table and 50 micron spot size of the carbon dioxide laser allow the laser workstation to produce patterns of features on glass wafers which can be mated to integrated circuit patterns on silicon wafers.

A RATFOR program has been written to control the workstation. Patterns of holes in 300 micron thick pyrex wafers have been produced. These 50 micron holes are to be aligned with electrical contact pads and integrated circuited in a silicon wafer to which the pyrex wafer is electrostatically bonded. The metalization of these vias is under test at present.

A mechanical Test Chip has been designed and laid out to test etching techniques for the pressure sensitive silicon diaphragm, sand-blasting and laser micromachining of the glass wafer, electrostatic bonding of the glass and silicon wafers, and cable connection to the device.

Signal processing and output format required for the integrated capacitive pressure sensor has been designed to switch the oscillator between reference and pressure sensitive capacitors. In addition to the sensed pressure, the circuit also produces temperature, pressure scale, temperature scale, and zero reference data, which provide all the information required for subsequent signal processing circuitry to calculate capacitance, and thus pressure, independent of temperature and drifts in offset or gain.

The pulse-period modulation of the output signal maximizes its immunity to noise, electromagnetic interference, and any progressive shunting of the output which may occur. Multiplexing these signals onto a single output line reduces the number of wires required by each sensor to 4.

This circuit has been designed, simulated, breadboarded, laid out, fabricated, and tested. A photomicrograph of the circuit appears in Fig. 1-8. The circuit is fully functional but more sensitive to temperature and supply voltage than desired. Therefore, the circuit and its fabrication process will be refined to reduce these dependencies and fabrication variations.

In applications such as this, which require many sensors, it is impractical to connect wires to each sensor individually. A significant simplification in wiring results if the sensor output signals are multiplexed in time. A multisensor Controller/Multiplexer (MC/M) integrated circuit that allows the ouput terminals from many silicon sensors to be fused together is currently under development. This integrated circuit will fulfill a variety of specifications.

Intelligent Systems for Robot Management and Vision

Intelligent Programming and Assembly

We have developed a new version of AL, a programming system which is portable among computers and between robots, and which demonstrates capabilities for programming manufacturing systems also. Under this contract, Goldman brought a new version of AL into operation and implemented major parts of the AL user interface, a syntactic editor and symbolic debugger. The new version included the following features: (1) graphics for forces and dynamics, new syntax to allow AL programs to make use of recently added abilities in the arm servo code, especially incremental motions, individual joint motions, and joint sensing; (2) reading force vectors from the force wrist in arbitrary coordinate systems; (3) a variety of new motion clauses to specify desired configurations such as straight-line (cartesian) motions; and (4) a SAY statement to access the speech synthesizer from AL programs.

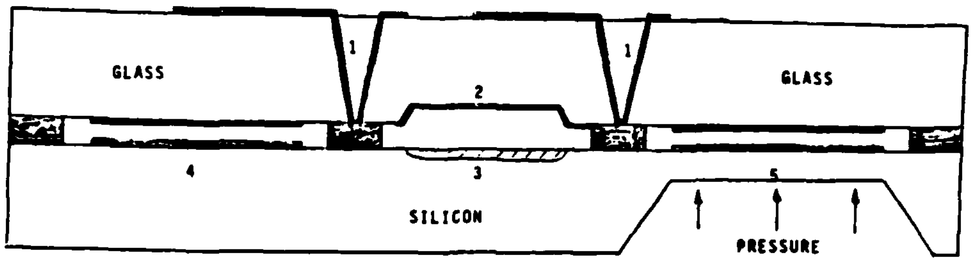
Initial implementation was done to bring up a distributed system version of AL. This is now up and running and will be ready to be used as an arm servo machine and on the ethernet, so that arm servos will be able to talk to an AL job running on another machine.

Assembly of an electric motor was performed by Goering using the IBM RS-1 robot, Fig. 1-9.

Obstacle Avoidance

A system for real-time collision avoidance was implemented by Khatib (report in preparation). The system is based on the use of potential functions around obstacles. Obstacles are described by composition of primitives which are approximately cylinders and blocks. The method requires a small amount of calculation; it allows obstacle avoidance to occur in real time as an integral part of the servo-control.

Previous research in obstacle avoidance has focused on the development of path planning algorithms, aimed at providing a free Cartesian path for the manipulator. A coordinate transformer generates the joint-



1. electrical contact vias
2. electrostatic shield
3. custom integrated circuit
4. reference capacitor
5. pressure sensing capacitor

Figure 1-7. Integrated Pressure Sensor Cross Section.

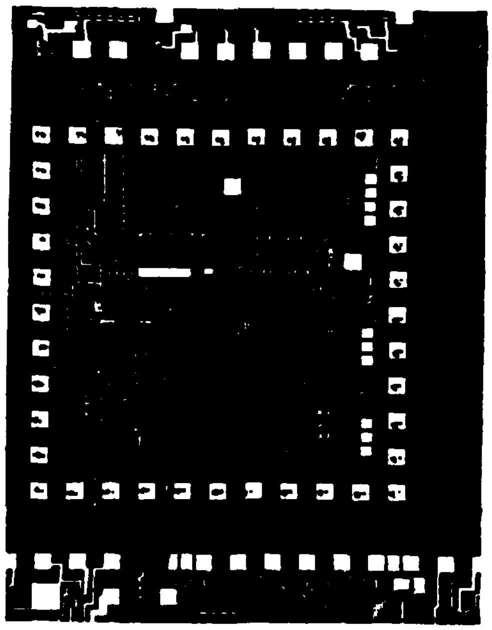


Figure 1-8. Capacitive Pressure Sensor Integrated Circuit.

space path for the servo-control level. The high complexitiy of computation in such approaches leads to serious problems in real time control of a manipulator meant to act in a complex and evolving environment.

We have developed a new control scheme based on the construction of a dynamic model of a manipulator in operational space (task-space) rather than joint-space. This allows a simple force transformation to replace the difficult conversion of the Cartesian path into joint coordinates. The philosophy of this approach is to say that the manipulator moves in a field of forces. The position to be reached is an attractive pole of the end effector, and obstacles are repulsive surfaces for the manipulator parts. Controlling a given point of the manipulator with respect to several obstacles is resolved directly by the addition of the relevant potentials.

An experimental manipulator programming system "COSMOS" (Control in Operational Space of a Manipulator-with-Obstacles System) has been designed for implementation of the method for the PUMA arms. Demonstration of motions with obstacles (including mobile obstacles) detected by an MIC (Machine Intelligence Corporation) vision module have been performed, Fig. 1-9.

Assembly Robot Tools and Subsystems

A dynamic simulator was implemented by Burdick. The simulator has been used in verifying analyses of control algorithms, and in Burdick's estimation of inertia and friction. The simulator is essentially a software equivalent of a robot arm. The simulator takes in torque commands from a control system program, and integrates the dynamic equations of motion (which are developed using Lagrangian mechanics) to yield joint accelerations, velocities, and positions. The simulator is currently set up to simulate the PUMA 560 robot, since most of the experimental work in controls at Stanford uses this robot.

An interactive graphics package has also been developed to plot the data generated from simulation. Involving the human mind to find patterns in visual data greatly improves the quality and efficiency of the data analysis. So far, the simulator has been used to test three adaptive control schemes, several dynamic control schemes, and two parameter estimation schemes—with considerable time saving as compared to implementing and debugging these schemes on a real robot arm.

A new, nonlinear, and generalizable technique has been developed that will continually monitor the parameters of a robot arm and update them as they change during operation. The technique measures the amount of torque applied to the robot during operation and tracks the robot's response to the input. Using the errors between the actual and desired trajectory and a general nonlinear model of the robot arm, the estimation scheme updates the parameter values. The technique has been succesfully applied to a physical single link robot.

Another technique has also been developed to estimate continuously the friction in robot joints. This system has also been simulated for a three link robot, and has been succesfully applied to a physical single link robot as well.

Work has been carried out on force sensing to support assembly. A joint effort with Unimation was done in part as a project for a course. (The sensor was fabricated under another contract). A patent has been applied for. Hake and others completed joint force sensing for one joint of the PUMA. Kirson designed a touch sensing finger which senses three components of force. An electronic interface for motors has been designed as one module for a general laboratory interface for mechanical systems.

Initial efforts have been made toward making an autonomous mobile robot operational. There is considerable interest in industry in automated transport systems with flexible navigation so that robots with mobility can service multiple machines and maintain a high rate of utilization. Our intent is to integrate manipulation with navigation.

Inspection and Vision

Research in vision has a focus on intelligent systems which support not only inspection and vision but the total robotics and manufacturing research program. Contributions have been made toward a successor for ACRONYM, an intelligent system developed at Stanford and adopted by about a dozen laboratories and companies (Brooks 82).

Work has been carried out in other areas of computer vision, including architecture of VLSI vision processors, segmentation with edge operators, graphics support, and hardware support.

Work on extending ACRONYM and developing SUCCESSOR has included several projects. A geomet-

Figure 1-9. Demonstration of Assembly Program Written for the RS-1 Robot: Assembling an Electric Motor.

Figure 1-10.

Obstacle Avoidance Program: Movement of a Simulated 4 d.o.f. Manipulator Inside an Enclosure.

ric editor has been designed and implemented by Rublee. Parts of the modeling system of SUCCESSOR have been designed and initial implementation has been begun by Cowan. The modeling system is greatly generalized over ACRONYM to include multiple naming, holes and set operations on volumes (union, intersection, difference). Binford, Brooks, Triendl, Dreschler, and Takamura are involved with the system design of SUCCESSOR. Research in generic models was carried out by Gray. An initial system and design of this system were done under other support.

Implementation of a new edge operator is being done by Triendl. Lim has made tests of shape from a shading algorithm by Pentland to assess its suitability for integration in ACRONYM or SUCCESSOR. Wells has begun design and experimentation toward building an active ranging device.

Both software and hardware support for vision systems have been provided. They include: software for interfacing the Grinnell display; LISP graphics by Selker; interface for an inexpensive TV input system by Imaging Technology Inc. by Wells; convolution software by Wells; TV time base corrector in progress by Rousso; an interface for an Optronics drum scanner by Fitzhugh; work on software for a GTCO digitizing tablet; and an interface for an image hardcopy output device.

JED is an interactive geometric model editor used for creating and editing three dimensional models of objects. The editor allows one to describe and display a wide range of generalized cones and orient these primitive shapes to form more complex assemblies.

Interactions and the New Center

The new Center for Automation and Manufacturing Science at Stanford has drawn us together in many ways during this first year, and has begun to attract a number of our talented colleagues to contribute in important ways to manufacturing technology. We have had a steady stream of visitors to our Center from many industries and from the world scientific community in robotics. We have taken part in several key invitational conferences with governmental research leaders in the field. And we have begun several new joint projects with industrial partners.

Within Stanford, the automatic control students of Professors Cannon, DeBra, Bryson, Breakwell, Franklin and Powell and the computer science students of Professors Binford, Brooks, and McCarthy — about 35 in all— are meeting regularly. With Air Force Center funding the assembly research part of Prof. Binford's laboratory has now moved to the Durand Building, colocated with the manipulator control research of Prof. Cannon's group.

In this same laboratory the new high precision manufacturing project (ONR funding) of Professors DeBra, Binford and Hesselink will develop its new machines. (The Laser Optical Processing Laboratory of Professors Hesselink and Goodman is across the hall).

Air Force Center funding to Professor Meindl, Codirector of Stanford's large Center for Integrated Systems, has formed a tie with that pioneering group in VLSI. We have conducted a series of seminars this year on future robot sensors, with Professors Meindl, Hesselink, Cannon, DeBra, and Kino. Professor Kino's well-known work in acoustic nondestructive testing suggests an excellent basis for developing acoustic proximity sensing for robots, which we hope the Center can initiate in the near future. We plan also laser optical sensors of various types, for manipulator and assembly tracking, in cooperation with Professor Hesselink's optics team.

Our connection with research groups outside Stanford are many and deep. Many of the leaders in robotics and automation did their doctoral or post-doctoral work at Stanford, about 40 are listed in Appendix C. In 1981-82, Professor Binford spent half-time at MIT. Victor Scheinman serves as a consultant to our Stanford Center, providing, in particular, engineering counsel at quarterly design reviews.

We have benefited very much from our participation in five significant invitational technical conferences in this first year:

- The Air Force/DARPA Robotics Workshop at Denver in March
- The Tri-Service Workshop on Manufacturing at Xerox in June
- The International Symposium of Robotics Research at Bretton Woods in August
- The DARPA Conference on Mechanical Innovations in Robotics at Menlo Park in October

This AFOSR project has contributed to making close contacts with several companies that facilitate technology transfer of the most effective kind: with people in joint efforts.

Professor Binford has participated with Honeywell, Unimation West (now Adept Technology Inc.), and SRI, Intl. in the Intelligent Task Automation program. Transfer of force sensing and control technology to Honeywell and Unimation West is occurring. The strong Stanford-SRI collaboration on model-based vision for the ITA program heavily uses Stanford's ACRONYM system. We have also collaborated with Unimation West in design and implementation of torque sensors for one joint of the Unimate PUMA 560.

A contract with IBM provides Stanford with two IBM robots (RS-1 and 7535) and involves close interaction with researchers at IBM, San Jose.

We are negotiating with Hewlett Packard for a joint effort in automation for semiconductor manufacturing. HP has contributed two computers for our work in manufacturing.

As Chairman for the General Motors Science Advisory Committee, Professor Cannon works with managers of the car divisions and the manufacturing development staff on the many forms of automation in their corporate-wide "factory of the future" program.

Center Support

General system support has gone to build up the facilities of the Center. A VAX 11/750 was purchased and augmented with a floating point processor and a 410 megabyte disk. A distributed computer environment is under development based on inexpensive SUN workstations operating over the Ethernet, using VAXes as file servers. The SUN workstations run the V kernel, developed at Stanford by Prof. Cheriton. The system runs both local programs and other programs such as LISP. This greatly expands our available compute power. Gray has developed a device-independent graphics package for SUN, VAX. Brooks and Narayanan have initial operation of a version of a COMMON LISP overlay for SUNs and VAXes. These elements combine to make a system which is cost-effective and powerful.

The Computer Science group has set up an assembly laboratory in Durand adjacent to the manipulator experiments of the Aeronautics and Astronautics department. The move must be accompanied by implementation of the computing environment described above, combining about 10 SUN workstations with VAXes over the Ethernet.

Future Plans

In the coming year we plan together to make progress and contributions in each of the basic areas of Fig. 1-2: in flexible-manipulator control, tactile sensing, robot high-level task management, and vision.

We plan to develop fast *simultaneous* control of the wrist and arm of Fig. 1-4, and with it demonstrate basic response capability for two-work-station scenarios, and also nonstop slew, snatch, and place.

We hope to achieve really good basic end point control of the two-link arm of Fig. 1-5, and demonstrate this capability in a number of tasks.

We hope to achieve adaptive control of the single, very flexible arm, demonstrating good control in the presence of large changes in payload at the tip.

We plan to carry out fabrication and test of the Test Chip we have designed for the pressure sensitive silicon diaphram, using several candidate laser micromachining and bonding techniques.

We will refine the sensor signal processing circuit of Figure 1-8 to reduce its sensitivity to temperature, supply voltage and fabrication variation. We will also continue development of the multisensor Controller/Multiplexer integrated circuit.

TECHNICAL REPORT

Introduction

The Stanford Center of Excellence is first a confederation of research leaders from two inernationally known groups at Stanford: the Robotics Group of Stanford's Artificial Intelligence Laboratory, and the Automatic Control Group of Stanford's Department of Aeronautics and Astronautics. The A.I. Lab has contributed heavily to robotics technology over the past 20 years, and has produced many leaders in robotics throughout the world. Stanford's Automatic Control Group includes the early developers of modern control theory, and has produced numerous aerospace industry leaders in guidance and control. Together we are finding there is much to learn from each other, and that we can do much together of a synergistic nature.

The common objective that we are addressing—that we have been led to by this major Air Force Support—is to advance the effectiveness of automation in manufacturing. We believe the next generation of flexible automation technology can contribute substantially to American productivity, and can thus provide important economic leverage for the Air Force—can truly contribute to the affordability of the operational systems the Air Force must have.

Our Center—the Center for Automation and Manufacturing Science (CAMS)—is the first of a new complex of centers at Stanford involved in the manufacturing enterprise: the Stanford Institute for Manufacturing and Automation (SIMA). The other founding Centers are CTRIMS, for graduate education in manufacturing operations, and the Center for Design Research (CDR) which will pursue creative use of the computer aided prototyping process. We expect the addition of other centers to SIMA—in metal formability, for example. We will also interact in many ways with existing centers at Stanford, such as the Center for Materials Research. As another example, Professor Meindl, a codirector of the large Center for Integrated Systems, is a principal investigator on this AFOSR Center of Excellence program. The interrelation between the autonomous Centers of SIMA is shown in Fig. A, where particular faculty are listed, along with sources of funding.

A central challenge in automation is to develop a new generation of robotic systems that are far more effective—more capable and more productive. Today's robots are heavy, rigid, crude, clumsy, blind and numb. They are either slow or have high power requirements. They must be taught by leading them through each task.

If the right *set of technologies* is developed, we believe the next generation of robots can, by comparison, be light, limber, deft, facile, friendly, quick *and* low-powered, seeing, feeling, thinking, machines. Above all, they will be capable of reasoning and strategizing—of carrying out tasks assigned at a high conceptual level, by "thinking through" the best way to carry out any given assigned task. Robotic devices with such characteristics and capability can provide the flexible automation that will be so important in achieving higher levels of productivity.

What are the underlying technologies that will be needed as the base for robots with such capabilities? They can be described in four catagories: manipulator control, sensing, thinking, vision, highly interrelated as depcited in Fig. 1-2. Among us, in our Center, we

are working to make useful contributions in all four technical areas. There is, of course, much interaction between, and synergism among the four areas; and that is the exciting thing about the level of effort that the AFOSR program makes possible.

Intelligent System Robot Management and Vision (Task 2)

Software is estimated to be about 90% of the cost of computer systems. Software has the same importance in computer controlled robots and in computer-integrated manufacturing. The Stanford A.I. Lab (SAIL) is a leader in programming systems for robots; its AL system is portable between computers and robots. AL integrates sensing, force control, and assembly primitives. It has a powerful user interface.

Intelligent systems will come to perform some of the planning tasks to simplify programming robots, including supervision of assembly operations, error detection and correction, planning paths around obstacles, choosing grasp locations, and choosing parts mating operations. The next generation of programming systems to extend AL is based on ACRONYM and its SUCCESSOR, developed at SAIL. Expert systems for manufacturing are expected to make a major impact. SAIL has been a leader in this area.

Assembly is expected to be the dominant robot application in the second half of the decade. Much of what is done in robotic assembly will carry over to more specialized automated assembly. Key issues in assembly include: 1) intelligent systems which maintain geometric models of parts and assemblies; 2) sensors; and 3) interpretation systems which transform sense data to information about parts and their locations. Force sensing and its integration into assembly is a major area of development for industrial robots. SAIL has led in development of force sensory control.

Industrial inspection may make a greater economic impact than robots. Inspection based on computer vision, other imaging sensors, and integration of multi-sensor data offers the promise of performing inspection which is not feasible with humans alone. Improved product quality, high reliability, documented compliance, and 100% inspection of safety-related items are some of the potential benefits. Inspection means more than scrapping defects. Inspection provides a way of quantifying performance of a manufacturing process to enable control of that process to produce improved product quality and to eliminate defects as much as possible.

Programming systems for inspection have the same importance as programming systems for general computers or for robots. SAIL has led the way with intelligent systems for inspection and vision, based on ACRONYM and SUCCESSOR.

Manipulators (Task 3)

Manipulators—arms and hands with their actuators, and the increasingly sophisticated feedback systems that control their movements—are the "business end" of a robot, where parts are mechanically moved, formed, placed, fitted together (or dismantled), and inspected. In our Controls Group we are addressing the question, not of how to make today's robot manipulators perform with greater speed and precision, but of how to provide manipulator control so good that a whole new generation of manipulators can be

developed— manipulators that are much lighter and far more facile than anything today's control systems could stably manage. To do this we have, in the manipulator control part of our research, turned our backs on present robots. Instead we have deliberately begun to develop a sequential family of new manipulators that are extremely light and flexible, deliberately exaggerating and exacerbating the control problem so that it will have to be solved in much more fundamental ways than it ever has before. Some members of our family of manipulators are shown in Fig. 1-3. It will extend, of course, in many ways not shown—to three dimensional action, and to mobile-mounted very flexible manipulator systems, for example.

By proceeding step-wise with the sequence of basic manipulator control problems indicated in Fig. 1-3, we expect to provide the fundamental new technology for controlling a new generation of lightweight flexible robots. At this point we have achieved precise control of the first three manipulator systems in Fig. 1-3 at speeds near the structural wave propagation limit, and we have completed construction of our first two-link arm, Fig. 1-3(d). Details of our progress in fast, precise control of non-rigid manipulators are given in the report section below on Task 3.

Sensors (Task 4)

New sensors will of course be extremely important components of new, more capable robots. In our early manipulator research we are using simple sensors—e.g., the light bulb/optical sensor shown in Fig. 1-3(a) and (c) in order to move Task 3 forward in parallel with the development of new sensors. At the same time, in Task 4 of this AFOSR program and in other projects, we are also sponsoring and collaborating with sensor development efforts.

The sensor system described under Task 4 of this report is for perceiving by touch, the shape or texture of objects. It will use an array—say 10 x 10—of pressure-sensitive silicon capacitive transducers, covered by a thin skin, as on a fingertip. Individual cells, each with its own integrated circuit, are about 1 mm. square, and prototypes are already operating. Sub-projects under Task 4 include mechanical development of the miniature silicon cantilever structures, multiplexing and processing the array of signals for "image" interpretation, and building the array into a "skin" suitable for future robot use.

While this (Task 4) tactile sensor is one of the most sophisticated sensor projects (drawing, as it does, on very recent advances in silicon integrated circuit technology), it is only one of several we look forward to using. Simpler touch sensors will surely be used on robots sooner. (As surrogate for these, we are currently using a thin whisker-with-strain gauge.) In the optical area, laser/fiber-optic systems of several arrangements are being thought about. Professor Hesselink is an expert in the area of optical sensing and optical processing, and is already working with Professors Debra and Binford on another CAMS manufacturing project. At this point we are replacing our light-bulb emitters with LED's, which we can multiplex to track simultaneously, for example, the end-points of two manipulators cooperating, or of a manipulator and its moving target.

We distinguish between optical sensing, where the desired point emits a signal that can be sensed as a point, and vision, which involves *interpretation* of a complex scene, as

described below.

We have carried on a series of small seminars on *proximity sensing* using acoustic techniques, with Professor Kino, a pioneer in acoustic non-destructive testing, and Professors DeBra and Hesslink as well as the four Principal Investigators (Binford, Cannon, Meindl, Brooks). This would give a local, *relative* measurement between a manipulator end-point and its target, to complement individual optical sensing of the two points separately. It appears possible to build arrays that will detect and relay general shape information as well as simply closest approach to a target; and this would be important to all of us.

Technical Report on Task 1

SURVEY OF KEY PROBLEMS AND TECHNOLOGY TRANSFER

Task 1 is important to us, for it is the means by which we can (1) be sure we are using our resources to contribute where it will count, and (2) connect our contribution to future operational designs that will be influential. The Center of Excellence support has allowed us to begin this process. It has also given us a leadership role in a broadly-based organization of manufacturing-related centers called the Stanford Institute for Manufacturing and Automation (SIMA). SIMA will work directly with a consortium of affiliated industrial companies, who will provide financial support and ongoing guidance to the Institute.

SIMA will encompass the design and management aspects of manufacturing as well as the areas of fabrication and assembly on which we are con- centrating. The founding centers of SIMA are CTRIMS, a graduate teaching program in Industrial Engineering, and CDR (Center for Design Research), in addition to our own Center (which is called CAMS—Center for Automation and Manufacturing Science). Existing Stanford centers, notably the Center for Materials Research, the Center for Integrated Systems, and the Graduate School of Business will also participate in SIMA activities, as Fig. indicates.

In developing our individual interactions with industry, we have moved deliberately in this first year, concentrating on areas where we already have something to "bring to the table." From this beginning we can be more effective in our survey of key problems.

This AFOSR project has contributed to making close contacts with several companies, contacts which facilitate technology transfer. Perhaps the best form of technology transfer is with people in joint efforts. This is the character of the developments described here.

Professor Binford has participated as a sub-contractor to Honeywell along with Unimation West (now Adept Technology Inc.) and SRI, Intl. in the Intelligent Task Automation program. There is a strong and active technology transfer in this program which is clearly evident in the transfer of force sensing and control to Honeywell and Unimation West. Much more transfer is expected. Indirect transfer is expected from the strong Stanford-SRI collaboration on model-based vision for the ITA program, which makes strong use of Stanford's ACRONYM system.

We have also collaborated with Unimation West in design and implementation of torque sensors for one joint of the Unimate PUMA 560. This contributes further to transfer of force sensing technology.

A contract has been arranged with IBM which provides Stanford with two IBM robots (RS-1 and 7535) for three years. The project involves close interaction with researchers at IBM, San Jose. The project includes assembly and analysis of assembly. It has already provided input into this program.

We are working out a basis for collaboration with Hewlett Packard. HP has already contributed two computers for our work in manufacturing. Arrangements are being negotiated for a joint effort in automation for semiconductor manufacturing.

Another major enterprise in which we have close collaboration is the General Motors Corporation. As Chairman for the General Motors Science Advisory Committee, Professor

Cannon has worked closely with managers of the car divisions and the manufacturing development staff as they address the many forms of automation in their corporate-wide "factory of the future" program.

Technical Report on Task 2
INTELLIGENT SYSTEMS FOR MANUFACTURING; INSPECTION AND VISION; SENSOR-BASED PROGRAMMING SYSTEMS

a. Intelligent Programming Systems for Robots and Manufacturing

We have contributed to implementation of a new version of a portable programming language for robots and manufacturing.

AL is a programming system for robots which is portable among computers and between robots. AL demonstrates capabilities necessary for programming manufacturing systems also. An interactive version of AL was designed and largely implemented before this contract. Under this contract, Goldman brought a new version of AL into operation and implemented major parts of the AL user interface, a syntactic editor and symbolic debugger. The new version included major bug fixes and new language features: graphics for forces and dynamics, new syntax to allow AL programs to make use of recently added abilities in the arm servo code, especially incremental motions (e.g. MOVE arm BY 2*xhat*inches); individual joint motions (e.g. MOVE arm[1] BY 10*degrees) and joint sensing; a FLOAT statement; reading force vectors from the force wrist in arbitrary coordinate systems; a variety of new motion clauses to specify desired configurations (e.g. WITH ELBOW UP), straight-line (cartesian) motions; a special statement to allow debugging of new features in the arm servo (passing arbitrary parameters to and from the servo from an AL program); and a SAY statement to access the speech synthesizer from AL programs. Other internal changes were also made.

Initial implementation was done to bring up a distributed system version of AL. This system support work includes: (a) bringing up the 11/60 for use in arm servoing; the 11/60 is now up and running (modulo a current disk problem) and will be ready to be used as an arm servo machine. and (b) putting both PDP11's on the ethernet so that arm servos running on the 11's will be able to talk to an AL job running on another machine. An ethernet device driver running under RSX has been written along with needed auxiliary programs such as a file transfer utility. Hall and Vistnes made initial efforts to port AL to VAX and SUN computers. Much remains to be done in porting to these machines. Software for automated self calibration in AL was done by Sathyanarayanan. At present, it is intended to store calibration results in files; this develoment awaits file input/output in AL.

A study was made by Selker of artificial intelligence approaches to the user interface, particularly utilizing a model of the user. The study did not lead to a design. The study had an educational payoff in that it lead to a seminar on user ergonomic interfaces. Lattanzi has worked on software to incorporate voice input with an Interstate Electronics board for the Multibus on a SUN workstation.

Work is proceeding on developing the next generation of programming systems for robotics and manufacturing. This work is based on ACRONYM and its SUCCESSOR. These are intelligent systems incorporating geometric modeling and geometric reasoning. These systems also support vision; they are described under the section on vision.

b. Assembly

Assembly of an electric motor was performed by Goering. Assembly used the IBM RS-1 robot. A videotape of the assembly has been made.

A system for real-time collision avoidance was implemented by Khatib [report in preparation]. The system is based on the use of potential functions around obstacles. Obstacles are described by composition of primitives which are approximately cylinders and blocks. The method requires a small amount of calculation; it allows obstacle avoidance to occur in real time as an integral part of the servo-control. The system is embedded in the COSMOS system. COSMOS, written in PASCAL and implemented on a PDP11/45 computer, has a servo-rate of 50Hz. Recent development in our work led to a new approach which is expected to give a servo-rate of 500Hz. Demonstrations of arm motions with moving obstacles have been done where object motion was detected by an MIC VS-100 vision module (Machine Intelligence Corporation). This approach was extended to control links of the manipulator with respect to different obstacles rather than controlling points. Obstacle avoidance is described below.

A dynamic simulator was implemented by Burdick. The simulator has been used in verifying analyses of control algorithms, and in Burdick's estimation of inertia and friction. The simulator is described below. Work has been carried out on force sensing to support assembly. A joint effort with Unimation was done in part as a project for a course. The sensor was fabricated under another contract. A patent has been applied for. Hake and others completed joint force sensing for one joint of the PUMA. Kirson designed a touch sensing finger which senses three components of force. An electronic interface for motors has been designed as one module for a general laboratory interface for mechanical systems.

Initial efforts have been made toward making an autonomous mobile robot operational. There is considerable interest in industry in automated transport systems with flexible navigation, for example Kommatsu, Japan. In applications such as machine loading and unloading, machining of parts takes considerable time. Robots are idle much of the time. Robots with mobility can service multiple machines and maintain a high rate of utilization. Our intent is to integrate manipulation with navigation.

Obstacle Avoidance

We discuss here the development of a unique obstacle avoidance scheme based on the use of potential functions around obstacles. With this scheme, collision avoidance, traditionally considered as a high-level planning problem, can be effectively distributed between different levels of control.

Previous research in obstacle avoidance has focused on the development of path planning algorithms, aimed at providing a free Cartesian path that enables the manipulator to accomplish its assigned task. A coordinate transformer generates the joint-space path executable at the servo-control level.

In previous approaches, the high complexity of computation involved in each of these stages leads to serious problems in real time control of a manipulator meant to act in a complex and evolving environment.

The control loop incorporating environment sensing feedback is, in fact, closed through the path finder and coordinate transformer. This will severely reduce the loop's servoing rate and by necessity restrict the manipulator's interaction with its environment.

Independently of the obstacle avoidance problem, we developed a new control scheme based on the construction of a dynamic model of a manipulator in operational space (task-space) rather than joint-space. This allows a simple force transformation to replace the difficult conversion of the Cartesian path into joint coordinates. A fundamental advantage of this approach is that the dynamic behavior of the system is controlled in the same space as the path's description, allowing an exact statement of error dynamics in Cartesian space.

This control approach enabled the development of a unique obstacle avoidance scheme based on the use of potential functions around obstacles, rather that planning paths. The philosophy of this approach can be schematically described as follows:

The manipulator moves in a field of forces. The position to be reached is an attractive pole of the end effector, and obstacles are repulsive surfaces for the manipulator parts.

Obstacles are described by composition of ***primitives***. Analytic equations representing envelopes best approximating the primitives' shapes have been developed, for instance:

$$\left(\frac{x-x_0}{a}\right)^{2n} + \left(\frac{y-y_0}{b}\right)^{2n} + \left(\frac{z-z_0}{c}\right)^{2n} = 1 \qquad \textit{for a parallelepiped}$$

$$\left(\frac{x-x_0}{a}\right)^{2} + \left(\frac{y-y_0}{a}\right)^{2} + \left(\frac{z-z_0}{c}\right)^{2n} = 1 \qquad \textit{for a cylinder}$$

It can be shown that these surfaces tend, respectively to a parallelepiped and to a cylinder of dimensions (a,b and c) and (a and c) when n tends to infinity. However, a good approximation of these primitives is obtained with n equal to 4.

The control of a given point on the manipulator vis-a-vis an obstacle is achieved by submitting it to a ***Force Inducing an Artificial Repulsion from the Surface*** (FIRAS, from the french). These forces are created by an artificial potential field V obtained as a function of the normal distance to the obstacle's approximating surface ρ:

$$V(\rho) = \begin{cases} \left(\frac{1}{\rho^2} - \frac{1}{\rho_0^2}\right)^2, & \text{if } |\rho| < |\rho_0|; \\ 0, & \text{if } |\rho| > |\rho_0|; \end{cases}$$

The artificial potential field V is designed to meet the manipulator stability condition and to create at each point of the obstacle's approximating surface a potential barrier which becomes negligiable beyond that surface. ρ_o represents the limit distance of the potential field influence.

ρ, the normal distance to the obstacle's approximating surface, is easily obtained by using a variational procedure rather than a direct resolution of the computationally complex geometric system of equations. In real-time control, this procedure does not require any significant additional computation. In fact, the distance's partial derivatives needed here are available in the potential field's gradient routine.

Controlling a given point of the manipulator with respect to several obstacles is resolved directly by considering the addition of the relevant potentials. Also, different points on the manipulator might be submitted to different obstacles' fields. Specifying an adequate number of such points enables the protection of all of the manipulator's links, as is shown in the following example:

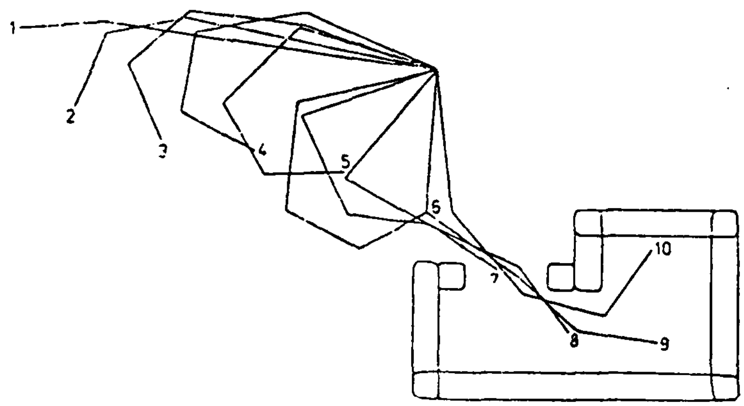


Fig. 2-1. Displacement of a simulated 4 d.o.f. manipulator inside an enclosure.

Considering the small amount of calculation needed, this method allows obstacle avoidance to occur in real time as an integral part of the servo-control.

An experimental manipulator programming system "COSMOS" (Control in Operational Space of a Manipulator-with-Obstacles System) has been designed at the Stanford Artificial Intelligence Laboratory for implementation of the presented control method for the PUMA arms. Demonstration of motions with obstacles (including mobile obstacles) detected by an MIC (Machine Intelligence Corporation) vision module have been performed.

This approach was extended to control links of the manipulator with respect to different obstacles rather than controlling points. This new development was implemented in COSMOS and motions of the PUMA involving its 3^{rd} link with an obstacle have been demonstrated.

COSMOS, written in PASCAL and implemented on a PDP11/45 computer has a servo-rate of 50Hz. However, the servo-rate limitation is not due to the amount of computation needed for obstacle avoidance, which is negligiable; rather, it results from the geometric and kinematic models' evaluations, which are necessary to produce the manip-

ulator end-effector position/velocity feedback.

Recent development in our work in that area led to a new approach based on the incorporation of a Cartesian state estimator. The expected servo-rate will be 10 times as great, *i.e.* 500Hz. This will contribut to a large improvement in the manipulator's dynamic behavior.

Collision avoidance, generally treated at the highest level of control, has been demonstrated here to be an effective component of low-level real-time control.

The obstacle avoidance problem might then be treated in two stages:

- generating in the high-level control system a global strategy for the manipulator's motion in terms of intermediate goals, rather than finding a complete free path;
- then producing at the lowest level, *i.e.* servo-level, the appropriate commands to attain each of these goals, taking into account the detailed manipulator/obstacle geometry and their respective motions.

By its nature, operational space control is well suited to both the stipulation and satisfaction of geometric constraints on arm movement, and the control of applied forces. This approach, and more generally all dynamic approachs, require effective force control. Incorporation of joint force sensing feedback is indispensable and research in this direction is currently planned.

Dynamic Robot Simulation

Motivation: A robot simulator is useful for a variety of purposes, the principal ones being: control system testing and debugging, control system research, and interactive robot design.

As robot control systems become more sophisticated and complicated, it is increasingly important to have flexible, reliable tools for debugging and testing new robot control systems off line. With a robot simulator, it is possible to test a new control system package with the simulator before actually using the new system to control a real robot. With the simulator, simple mistakes, such as a misplaced sign in a torque calculation, as well as more complex mistakes in system timing and organization can be found and corrected before a control package is installed. In this manner, damage to the robot as a result of faulty control system software can be prevented. In a research environment, many people may be using the the same robots for different research projects. Damage to a robot can impede the progress of other research projects and must be avoided. Since a simulator is strictly software which is easily replicated, many people can work on control system projects simultaneously without actually having to have a robot arm available. With the simulator, the capability of a research lab can be extended without a lot of additional cost.

The simulator is valuable for control system research for some of the same reasons mentioned above. Robots are highly nonlinear dynamic systems, and the theory of nonlinear control is still not well developed. The simulator is a convenient tool for rapidly testing new theories in nonlinear, dynamic, and adaptive control. Here again, the simulator prevents damage to real robots if the new control scheme is unstable.

In some situations, testing new control theory with a simulator is superior to testing the theory with a real arm. The simulator has well known and controllable parameters. Thus, new control schemes can be tested under a variety situations and conditions and certain parameters can be changed in a prescribed manner to examine the effect of the parameter changes on the quality of the control scheme. For example, the kinematic parameters of most robot arms are well known, but the dynamic parameters (such as the moments of inertia of each link of a robot arm) are usually not known very accurately. The errors in the parameter estimates will have some effect on the quality of control. With the simulator, all of the dynamic parameters are well known. The values of the dynamic parameters used in the simulated control system can be varied from the true parameters in a systematic way to investigate the effect of parameter error. The controllable nature of the simulator is also useful for comparing and contrasting the capabilities of many different control schemes under a variety of conditions.

The simulator can be useful for many "what if we had this type of information available" situations. For example, the PUMA 560 robot does not come equiped with joint velocity sensors or joint torque sensors. With the simulator, virtually any kind of sensor can be simulated, so that new types of control schemes that may require these types of sensors can be investigated.

A dynamic simulation of a robot is a powerful tool for interactive robot design as well. A general model of a new robot design can be implemented in the simulator; the designer can vary parameters such as the mass of a joint or the maximum torque of a motor or the length of a joint, and examine the effect on the arm performance. With the simulator, an optimal set of parameters can be developed before arm construction is started. The robot designer can also check that a particular configuration will meet desired specifications before construction of the arm begins.

Description of the simulator: The simulator is essentially a software equivalent of a robot arm. The simulator takes in torque commands from a control system program, and integrates the dynamic equations of motion (which are developed using Lagrangian mechanics) to yield joint accelerations, velocities, and positions. These quantities are then returned to the control program to complete the feedback loop. Different versions of the simulator have been developed: the simulated arm and the control system can be on different computers and communicate over a network, or they can be on the same computer. The simulator is currently set up to simulate the PUMA 560 robot, since most of the experimental work in controls at Stanford uses this robot.

As previously mentioned, for maximum flexibility the simulator parameters can be varied by the user. In addition to changing the kinematic and dynamic parameters,the simulator user can also change many other options. Currently the user can change:

1. Amount and types of friction at each joint of the arm. Real arms have friction in the joints, and so an accurate arm simulation should have friction also.
2. Actuator dynamics and saturation. All real motors have some dynamic behavior and a maximum torque output. The motor dynamics and motor torque limits can be specified by the user.

3. Sensor and Actuator noise. Sensors are subject to quantization, round-off error, electronic noise and other instrumental noise. Uncertainties in motor currents and torque response also are usual. These uncertainties can seriously affect control system behavior. The uncertainites can be specified by the user.

The user of the simulator can store a variety of data generated during the simulation for later analysis. The type of data stored can also be specified by the user. For example, the simulator user may want to store the time history of the motor torques during execution of a simulated trajectory.

To facilitate analysis of the data, an interactive graphics package has also been developed to plot the data generated from the simulation. In our experience, the capability of the human mind to find patterns in visual data greatly improves the quality and efficiency of the data analysis.

Previous Simulator Uses: So far, the simulator has been used to test three adaptive control schemes, several dynamic control schemes, and two parameter estimation schemes–with a considerable time saving as compared to implementing and debugging these schemes on a real robot arm.

Parameter Estimation

Motivation: As most advanced control systems (in research institutions) are moving towards some type of dynamic control, it is very important to have good measurements of the dynamic parameters of the robot arm to be controlled. The quality of the control system will be affected by errors in these values. It is easy to measure the mass of each link of the robot arm. However, it is difficult to directly measure the inertial properties of an arm. Since most robot manufacturers have not been concerned with dynamic control, the required inertial information is not available from manufacturers. In addition, other quantities such as joint friction are not easily measured, but are important factors in robot performance. Hence, it is desirable to develop methods, based on control theory, to derive the inertial and friction parameter values. There are two possible scenarios for parameter estimation. In the first application the estimation is done off-line and can be considered a calibration technique. In this scenario, before the arm is put into service, the arm is subjected to a parameter estimation procedure, and the resulting inertial and friction values derived from the procedure are permanently programmed into the robots memory. In the second scenario, the robot continually monitors the values of the parameters, and updates them as they change. The changes could be due to aging of the robot parts, or changes in temperature, or changes in the load that the robot is carrying. As the robot picks up and releases objects or as different tools are mounted, the dynamics properties will change. It is desirable for the robot to continually monitor its own parameters and update them as necessary. Continuous estimation is also crucial to many adaptive control schemes.

Although parameter estimation techniques have been developed for linear control systems based on linear control theory, these techniques have not had good success when applied to nonlinear systems, such as a robot.

Current Results: A new, nonlinear, and generalizable technique has been developed

that will continually monitor the parameters of a robot arm and update them as they change during operation. This technique was derived using Lyapunov stability theory for nonlinear differential equations. In summary, the technique measures the amount of torque applied to the robot during operation and tracks the robot's response to the input. Using the errors between the actual and desired trajectory and a general nonlinear model of the robot arm, the estimation scheme updates the parameter values so as to drive the trajectory error to zero. Not only does the estimation scheme update the parameters, but it also performs adaptive control. So far, this scheme has been simulated (using the simulator described above) for a single link and a three link robot with great success. The technique has been succesfully applied to a physical single link robot as well.

Another technique has also been developed to estimate continuously the friction in robot joints. Good estimates of the joint friction allow friction compensation in the control system, which improves performance. This system has also been simulated for a single link and three link robot, and has been succesfully applied to a physical single link robot as well. Currently, we plan to extend both methods to the control of a real three link robot, and eventually to a six link robot.

c. Inspection and Vision

Research in vision has a focus on intelligent systems which support not only inspection and vision but the total robotics and manufacturing research program. Contributions have been made toward a successor for ACRONYM. ACRONYM is an intelligent system developed at Stanford and adopted by about a dozen laboratories and companies [Brooks 82].

Work has been carried out in other areas of computer vision, including architecture of VLSI vision processors, segmentation with edge operators, graphics support, and hardware support.

Work on extending ACRONYM and developing SUCCESSOR has included several projects. A geometric editor has been designed and implemented by Rublee. Parts of the modeling system of SUCCESSOR have been designed and initial implementation has been begun by Cowan. The modeling system is greatly generalized over ACRONYM to include multiple naming, holes and set operations on volumes (union, intersection, difference). Binford, Brooks, Triendl, Dreschler, and Takamura are involved with the system design of SUCCESSOR. Research in generic models was carried out by Gray. An initial system and design of this system were done under other support.

Implementation of a new edge operator is being done by Triendl. Lim has made tests of shape from a shading algorithm by Pentland to assess its suitably for integration in ACRONYM or SUCCESSOR. Wells has begun design and experimentation toward building an active ranging device.

Both software and hardware support for vision systems have been provided. They include: software for interfacing the Grinnell display; LISP graphics by Selker; interface for an inexpensive TV input system by Imaging Technology Inc by Wells; convolution software by Wells; tv time base corrector in progress by Rousso; an interface for an Optronics drum scanner by Fitzhugh; work on software for a GTCO digitizing tablet; and an interface for

an image hardcopy output device.

JED a Geometric Model Editor

JED is an interactive geometric model editor used for creating and editing three dimensional models of objects. The editor allows one to describe and display a wide range of generalized cones and orient these primitive shapes to form more complex assemblies. Generalized cones refer to a class of objects formed by defining a planar cross-section to be swept along an axis or spine. For example a circular cylinder is formed by sweeping a circle along a straight spine. Additionally the cross-section can be deformed as it is swept along the spine. Normally this takes the form of a linear scaling in one or two directions in the plane of the cross-section.

The user interacts with the editor through menus, keystrokes, and extended commands. The current model is displayed using a polyhedral approximation of the object.

In creating a model the user will initially create the primitive objects that will be combined to form the assembly. The primitive objects are created by selecting the spine type, cross-section type and the sweeping function from menus displayed on the screen. After the above selections have been made the user enters the spine, cross-section, or sweep command to specify the parameters for the selected types. For example if a straight spine were selected the parameter to specified would be the length of the spine. Similarly the parameters for a rectangular cross-section are height and width. Finally a command to make the object from the currently specified types and parameters is issued to create the object and display it at the current location and orientation of the cursor.

Shapes may be combined to form more complex assemblies by specifying relationships between features of the primitive objects. The user selects features of an object by using keystroke commands to position a cursor over the feature and pressing the feature select key. An extended command can then be issued which specifies the relation between the currently selected features. The selectable features are edge, faces, vertices and spines. Relationships include flush, aligned, parallel, perpendicular and at an angle to. The user can either use the default values for the remaining degrees of freedom or specify one's own values. At this time multiple relationships are not supported.

The design of the editor facilitates addition of new commands and shape descriptions. Keystroke functions, extended commands, and shape definitions are stored in records. The editor modules use these record definitions when reading the keyboard, executing extended commands, and creating shapes. The functionality of the editor can thus be extended or modified by creating more records. The record definitions can be loaded at runtime, thus limiting the changes needed to the internal code.

This editor provides improvements over two previous editors developed here: MODITOR and GEOMED. MODITOR, and editor for editing ACRONYM models, allows a user to traverse the acronym subpart hierarchy and textually change the slots of the model description. It is best used to change the slot values of an existing model rather than inputing a model from scratch. Specifying relative positions between subparts in ACRONYM models requires specifying a translation and a rotation. Translations are specified using a 3D vector and rotations are specified by the axis of rotation and an angle about this axis. For

simple positions and orientations this is adequate. However in the case of non orthogonal orientations this method often becomes difficult. JED alleviates this difficulty by allowing users to speacify relations between features on the objects and computing orientation from the specified relations. Additionally, the class of generalized cones has been extended over those available in ACRONYM and MODITOR. GEOMED developed by Baumgart, used winged edge polyhedral to represent objects and provided the user with a powerful set of keystroke commands for user interaction. These commands provided the user with a powerful set of functions to form complicated polyhedral objects. For an experienced user many complicated models could be created easily. JED, on the other hand, is aimed at the novice and infrequent user, therefore, requirements on the user's memory are kept to a minimum by using menus and a small set of keystroke commands.

d. Center Support

General system support has gone to build up the facilities of the Center. Much of our computing is now on a VAX 11/780, obtained at a 50% credit from DEC. A VAX 11/750 was purchased under this contract at a special price. It was augmented with a floating point processor and a 410 megabyte disk (System Industries controller with Fujitsu Eagle disk). Sathyanarayanan has supervised its introduction. DEC is still bringing it into operation.

A distributed computer environment is under development based on inexpensive SUN workstations without disks operating over the Ethernet, using VAXes as file servers. The SUN workstations run the V kernel, developed at Stanford by Prof. Cheriton. The system runs local programs when they run on the SUN and other programs such as LISP on the VAXes. All this is transparent to the user. In actuality, a large part of computation can be done locally, e.g. EMACS, C and PASCAL programs. This greatly expands our available compute power. Gray has developed a device-independent graphics package for SUN, VAX based on the Stanford VGTS (Virtual Graphics Terminal System) which is based on the V kernel. Brooks and Sathyanarayanan have initial operation of a version of a COMMON LISP overlay for SUNs and VAXes. These elements combine to make a system which is cost-effective and powerful.

Effort has gone into setting up a laboratory in Durand in space provided by the Guidance and Control Laboratory of the Aeronautics and Astronautics department. Further space has been made available in Cedar Hall. Wells has played a major part in planning and arranging the move. The move will make necessary the implementation of the computing environment described in the previous paragraph, combining about 10 SUN workstations with VAXes over the Ethernet. Setting up this laboratory will solve our long-standing space problems at the cost of considerable effort and system building to replace facilities which were available in our current location.

Technical Report on Task3:
RAPID, PRECISE CONTROL OF NONRIGID MANIPULATORS

Overview

The underlying objective here is to develop the sequence of technologies that will enable future generations of robots to move much more quickly, more deftly, than today's robots, achieving much higher levels of precision, while at the same time removing the need for robots to be the heavy, rigid, power hungry machines that today's robots are.

Toward this objective, we are pursuing a sequence of specific projects, each with specific capability goals to be demonstrated, that will provide key elements of the desired new robot technology base. The AFOSR Center of Excellence level of funding has made it possible for us to make major advances this year, both in technological capabilities achieved and in the development of experimental facilities and expertise needed to carry on advanced research in this area.

Typical of the new facilities is the experimental two-link arm with flexible tendons, which was completed this year with AFOSR and DARPA funding, and on which we are now beginning a comprehensive sequence of increasingly difficult experiments that will lead to demonstrations of more sophisticated robot control capabilities.

The flow and interaction of our projects is indicated in Fig. 3-1. The first fundamental experiments on the two-link arm will all be AFOSR projects.

To provide a helpful overview, Fig. 3-1 includes early manipulator projects that preceded the AFOSR Center of Excellence Funding and mutually supporting projects that are funded from other sources. Each box in Fig. 3-1 (e.g., "Flexible Arm with Wrist") is a major experimental configuration on which a sequence of new control capabilitites is being (or will be) developed. The double boxes are AFOSR funded projects. Each new capability (e.g., "End Point Control"") achieved with a given configuration is invariably based on extending what was learned first with an earlier, simpler configuration; and each of these new capabilities will be crucial to several that follow. Thus, the Center of Excellence Funding allowed us this year to bring the flexible manipulator with wrist configuration from first conception thru design and fabrication and assembly to a working system on which early successful experiments with end-point control have already been accomplished. But this rapid progress was based firmly on the earlier step-by-step development of the single very-flexible manipulator, with its optical tip-position sensor and its pioneering end-point feedback control. (And that control, in turn, was able to draw on the earlier achievement of noncolocated control of the very-low-ς disk system.)

In future, the capabilities—of end-point control using two actuators in concert and of obtaining coarse-fine precision—that will be developed first for the flexible arm with wrist, will then form the technical base for the major series of developments planned with the new two-link manipulator facility: experiments with control in two dimensions, with first optical, then force control; experiments with two arms plus double wrist; experiments with target tracking and rendezvous leading to a pair of two-link manipulators cooperating to perform higher-level tasks. Note that both well-developed force control (of a flexible manipulator tip) and task programming will also be essential supporting capabilities at

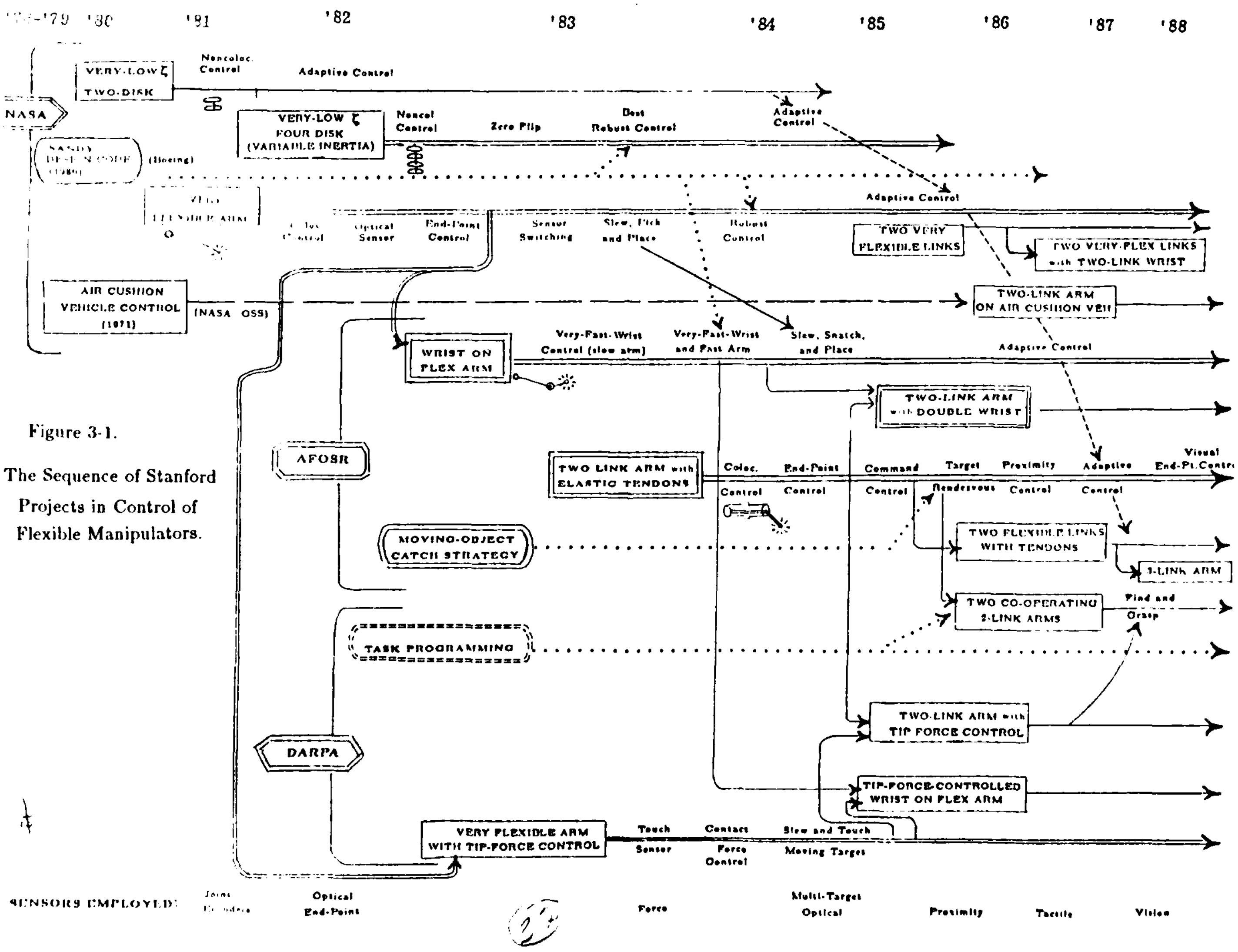
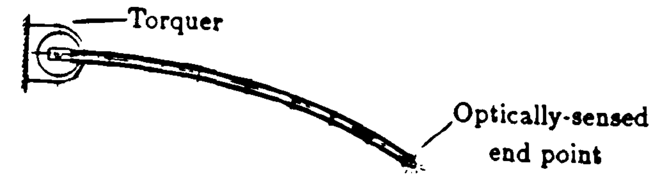


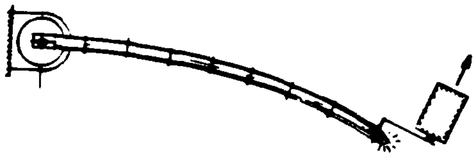
Figure 3-1.

The Sequence of Stanford Projects in Control of Flexible Manipulators.

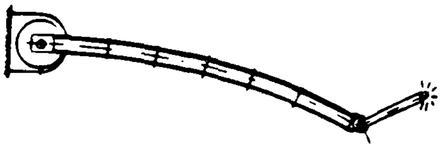
(a) Very flexible one-link manipulator
(Rapid pick and place)



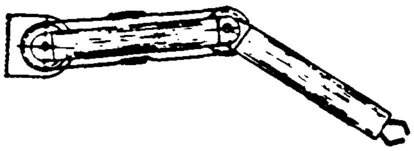
(b) Very flexible manipulator with force control
(Slew and touch moving target)



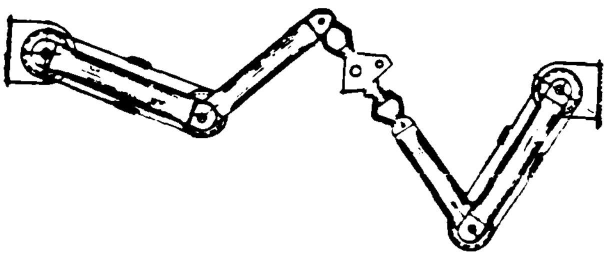
(c) Flexible manipulator with fast wrist
(Precise snatch and place)



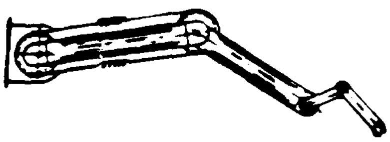
(d) Two-link Arm with Elastic Tendons
(2D pick and place)



(e) Cooperating Two-Link Arms
("Long-Part" handling)



(f) Two-Link Arm with Double Wrist
(Very fast, precise 2D tasks)



(g) Two-Flexible-Link Arm

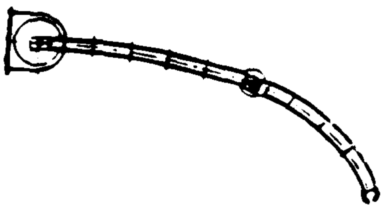


Figure 3-2. The Sequence of Experimental Very Flexible Manipulators.

this point; and they too will be available from other, concurrent projects, as Fig. 3-1 shows.

As Fig. 3-1 indicates, the Two-Link Manipulator that we have designed and built this year with AFOSR and DARPA support will be (with its derivatives and augmentation) a major facility for a sequence of developments and demonstrations that will make more directly usable, by robot designers, the quite fundamental control advances we have been able to achieve.

A most important fact is that the gratifyingly rapid progress we have been able to achieve in each of the projects in Fig. 3-1 is due in great measure to synergism with the other concurrent projects in whose midst it exists. *The major AFOSR Center of Excellence support, together with the other funding indicated in Fig. 3-1, has made possible a critical mass of talented people and new equipment and activity, without which many of the achievements of this year would simply not have occurred at all, let alone so quickly. The presence concurrently of all these people is what made these achievements happen.*

Again, the basic generic thing that we have been able to do (and be the first to do) is control very light, flexible manipulators in swift, purposeful motions: control position and force at their tips by measuring these quantities directly and feeding them back. As the sequence of projected project milestones in Fig. 3-1 unfolds, we aim to build a deliverable set of experimentally demonstrated fundamental robot-control-system design technologies that commercial designers can apply to the next much more capable generation of robotic systems.

Details of progress in three main-stream AFOSR supported projects in Fig. 3-1 are given in the sections which follow.

a. Very Flexible Manipulator with Wrist*

Description

This new system developed by Wen Wie Chang is shown in Fig. 1-4 and 3-2, (Fig. 3-2 is a repeat of Fig. 1-6, for convenience.) The wrist, a short link 6.5 inches long, is installed at the tip of a 97 cm. flexible beam. The wrist is light and rigid compared with the flexible beam. The motion of the wrist is controlled by a DC motor at the axis joining the wrist to the tip of the flexible beam. A lamp is mounted at the tip of the wrist to indicate the end point position where an end effector will be mounted. (A gripper will be the first end effector to perform some pick and place tasks.) A silicon photo sensor mounted above the apparatus is used to sense the position of the lamp and provide a tip-position signal for the controller.

A Rotational Variable Differential Transformer (RVDT) is mounted at the wrist motor axis to measure the relative angle between the wrist and the flexible beam. A DC brushless

* This project contributes to fulfillment of tasks n, o, and p of the AFOSR Contract: "n. Extend the end-point control laws developed for single link flexible arm operation to two link operation in the horizontal plane; o. Investigate the capabilities and limitations of lumped-compliance robot arms; p. Extend the work in tasks n and o to robot arms with distributed flexibility."

motor located at the hub of the flexible beam is used to control the large motion of the beam. Along the side plate of the flexible beam, four pairs of strain gauges are mounted and some of them will be used to provide information about the vibration modes of the beam for the purpose of system control. A potentiometer colocated with the hub motor measures the hub displacement of the flexible beam relative to the fixed base.

The system has two rigid body modes which need both motors to be fully controlled. The first two vibration modes have been indentified at 2.0 Hz and 3.9 Hz, and higher modes may be neglected in the system analysis and controller design unless much higher accuracy is required.

This system provides an experimental test bed with which to study the linear interaction between two links with one of them having distributed flexibility. It can also be used to test how much improvement in the slew speed, end-point settling time, position accuracy and contact-force can be achieved with the redundant degree of freedom associated with the smaller, faster, local wrist.

Rationale

The importance of using an end point sensor to control a flexible manipulator has been described previously .

When a robot manipulator is used in either a fabrication or assembly job, the area of a working station is usually small compared with the reachable region of the manipulator, over which parts are moved from station to station. To achieve the most efficient operation, the manipulator has to slew rapidly from station to station, but at the same time be able to perform tasks within a station under accurate, very-high-bandwidth control.

A rigid and heavy manipulator cannot achieve high speed and bandwidth with a reasonable amount of power consumption. A lighter manipulator can be moved faster when its flexibility is under proper control; but the maximum bandwidth of the closed-loop, and the precision it can achieve, is still limited by its flexibility, ultimately by its wave propogation time, as we have shown. A micro manipulator carried at the end of a larger arm can greatly enhance system performance by providing a way to achieve very high band- width and precise end point motion within a working station, i.e., within the immediate vicinity of the end of the larger manipulator.

An interesting thing to study in a fundamental way is the interaction between a micro manipulator and its carrier, the larger manipulator, especially when the latter one is built light and flexible. The skillful integration of those two will achieve the goal stated above without compromise, and is the subject of this current research.

The experimental setup of Fig. 3-2 (and Fig. 1-4) consists of a short and light-weight but still rigid wrist, representing the micromanipulator, working with a one dimensional flexible beam. This will be the test bed for studying very fast and accurate tip position control. The setup can also be used to investigate the interaction between an articulate hand with a moving flexible robot arm.

Tasks to be Performed:

Tasks (1) and (2) have now been completed, as described below. The others are to follow.

(1) Accurate tip position control with high bandwidth when the tip position is sensed by an "End Point Sensor".

(2) Very fast, precise command following by wrist tip (lamp position) within local work area, with slow following by large flexible arm.

(3) Very fast, precise command following by wrist tip (lamp position) within local work area but with simultaneous optimal fast (near wave-propagation limit) control of the flexible arm. The wrist local motion will still be much faster than the flexible arm can move; but this will optimize their combined motion, and represent an important advance: control optimization for a two-input, one-output end-point controlled system.

(4) Target tracking and tip velocity control.

(5) Smooth transition for the system to move from outside into the field-of view of the end point sensor.

(6) Quick and smooth transition from large motions to fine motions.

(7) Snatch-and-Place while the flexible beam is still moving.

(8) Contact force control through the proper simultaneous control of the wrist and arm motors.

During the design of controllers to perform these various tasks, different design methods will be studied and compared, based on their performance, complexity and robustness.

Results to Date

Fabrication and assembly of the Beam-Wrist system was completed in 1983. A frequency response test was performed to verify the mathematical model that had been developed. Because of the Coulomb friction and cogging torque of the wrist motor, the parameters of the system associated with the wrist cannot be identified accurately by tests alone. Therefore, theoretical analysis is being used, together with the test data, to get a mathematical model.

The analysis shows that when a wrist-and-flexible beam system is designed properly, the transfer function from the wrist motor to the wrist tip position will have alternating poles and zeros on the imaginary axis, with two poles at the origin. (Even though the tip position sensor is not really colocated with the actuator, the wrist motor, there is no flexibility between them.) The identified system model agrees with this analytical prediction, and this property is used when designing the high-gain control loop closing the wrist motor and tip position sensor. This inherent alternating pole and zero pattern on the imaginary axis guarantees the stability (and robustness!) of the closed loop when a lead compensator is used.

A simple digital controller has been implemented on an RT-11/23 mini- computer

with 100 Hz sample rate. The wrist-motor-to-tip-position-sensor loop is closed with a high gain lead compensator, and the colocated hub motor and pot are used with a low gain lead compensator to close the other control loop, for the flexible beam.

Figure 3-2d shows the test result of response to a step command of both the wrist-tip position and the end of the flexible arm. The accuracy of the tip position is about 1 to 2 mm, which is a reasonable value with the current photo sensor setup. The fast tip response with excellent stability that is achieved experimentally agrees with the results predicted from the alternating pole and zero pattern.

Note (Fig. 3-2d) that the wrist tip (where a working tool would be) gets to the new commanded location in space in only 150 milliseconds, and stays there while the slower flexible arm catches up in about 1500 milliseconds (related to its bending-mode frequency). It is a striking thing to watch the lighted tip snap to its new position in space, and stay precisely there despite movements of the rest of the system. We consider this a major achievement. When this result is translated to an industrial application, all the time intervals in Fig 3-2d can be expected to be at least 10 times faster: and this has very important implications for high speed in assembly operations.

As the next task in this project (Task 3 above), an LQG optimal control design method will be used to achieve good tip control simultaneously with a fast control loop for the flexible beam.

To reduce the effect of nonlinear friction from the wrist motor, a study will also be conducted to investigate the feasibility of dynamic torque control, using a torque sensor to measure the actual torque output from the motor. At the same time, an investigation is being conducted to see if a better wrist motor can be used to reduce the friction torque in order to make the system more linear, so that it can be modeled more accurately. An accurate linear model can take advantage of using LQG optimal design methods which result in high bandwidth controllers in general.

b. Two-Link Manipulator with Flexible Tendons*

Description

Figure 3-3 is a drawing of the two-link rigid arm with flexible tendon drives, which has been developed by Michael Hollars. The arm was designed to have minimum weight yet be very stiff by using aluminum tube and shell constuction. The motors and gearing were sized such that the unloaded arm can move between any two points in its operational envelope within one second. Each link is one-half meter long and the shoulder joint has a range of ±90 degrees and the elbow joint has a range of ±120 degrees. The arm was designed to have a payload to arm mass ratio of about one. The large payload capability combined with the ability to change the springs in the tendon drives gives the system a very wide range of plant dynamics, and thus the two-link arm should prove to be a very powerful and useful experimental tool in the study of end-point control of flexible manipulators.

* This project contributes to fulfillment of tasks n. and o of the AFOSR Contract: "n. Extend the end-point control laws developed for single link flexible arm operation to two link operation in the horizontal plane; o. Investigate the capabilities and limitations of lumped-compliance robot arms."

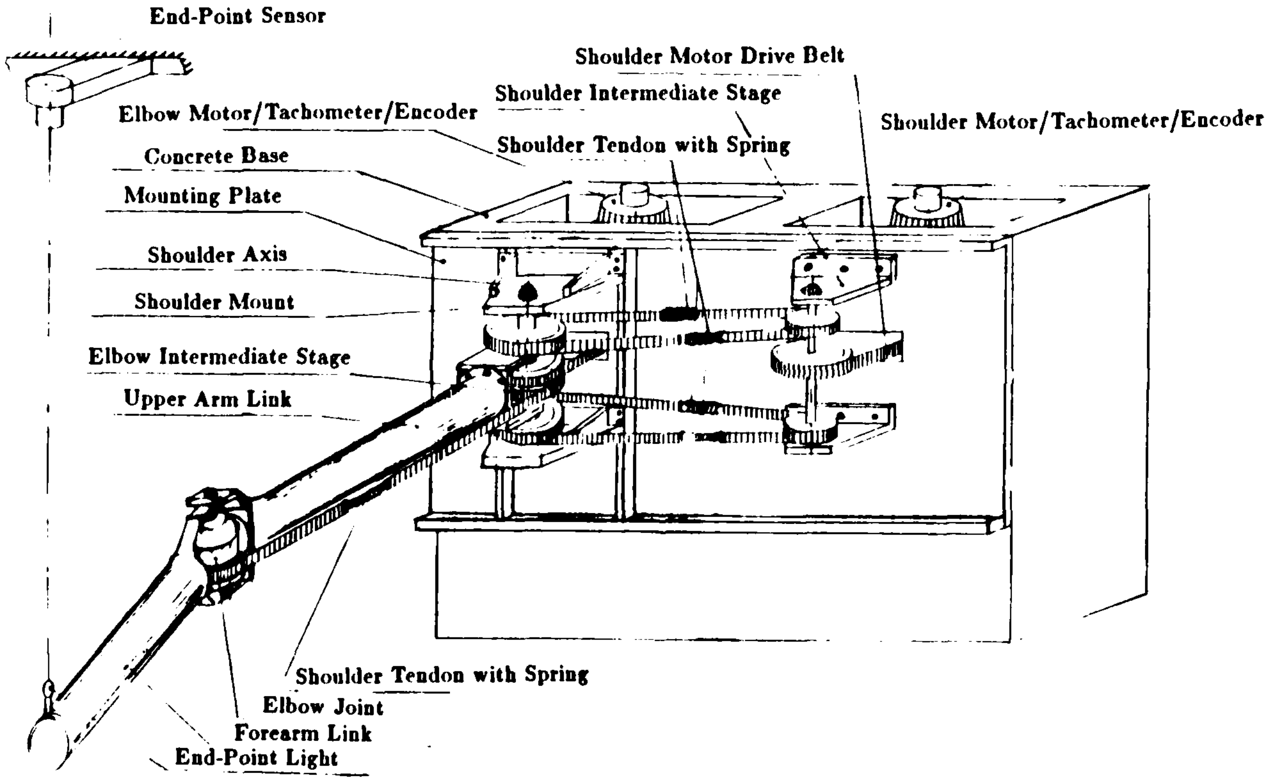


Figure 3-3. The Stanford Two-Link Arm with Flexible Tendons.

Rationale

Extending the end-point control laws from one to two links (Fig. 1-3) introduces two significant complications. First, the system is now strongly nonlinear. The inertia of the manipulator as seen from the shoulder joint is a trigonometric function of the elbow joint angle. Second, the system is multi-input, multi-output with significant coupling between the links (especially at high velocities where Coriolis and centripetal accelerations are large).

Since the extension to multi-link end-point control introduces these complexities, we have designed a set of experiments (see Fig. 1-3) that will gradually introduce these complications and those of mechanical flexibility. The first experiment in the series was, of course, the one-link flexible arm with distributed flexibility in the link itself; and the second is the flexible arm with wrist, described in the preceding section.

The third experiment now entering study is a rigid two-link arm with lumped flexibility in the form of linear springs inserted in the tendon belt- drive train. The fourth experiment will be to replace the outer rigid link with a flexible beam similar to the one-link arm. The system will then be a combined lumped and distributed flexibility arm. Finally, the entire arm will have flexible linkages. In each case, the arm will be tilted from the horizontal plane for some experiments to introduce a component of gravity into the system. Further, future derivatives of the two link manipulator are indicated in Fig. 3-1.

Status

The major accomplishment in this first year has been to design and construct the flexible two-link-arm facility. This is a major facility for us, taking us from one-dimensional to true two-dimensional research in robotics. It will serve in the coming few years as the test bed for a main-stream sequence of experiments and demonstrations in fast, precise end-point control of flexible manipulators.

The first two-link arm is now built and equipped with flexible tendons (flexibility can be varied) and DC drive motors. At this point we have:

(a) begun open-loop vibration tests to verify our mathematical models of the system.

(b) accomplished closed-loop control using sensors colocated at the motors.

(c) installed an optical tip sensor, and begun tests on it.

In the coming months we shall begin our experiments with end-point control in two dimensions.

Plans for End-Point Control

The lumped compliance robotic arm to be controlled first is the two-link rigid arm with flexible tendon drives described above. Since the arm has just been constructed, the work in this section has just begun. Thus far, only limited simulation studies and control system designs have been completed. We have six candidate areas of control laws we plan to investigate:

1) Successive loop closure of rate and position of each joint. This is the common type of control used in industry today. We have implemented this controller on the two-link arm to demonstrate the inadequacy of this type of control for systems with flexible modes within the bandwidth of the controller. All of the following approaches will use end point sensing.

2) Constant-gain robust controllers. New controller design programs that can find robust controllers for systems with multiple plant conditions have been developed at Stanford (especially the SANDY code noted in Fig. 3-1). In our case, the multiple plant conditions are the extremes of the elbow joint angle and payload mass. The technique guarantees stable control for all plant conditions (hence, robustness). However, performance is invariably degraded.

3) Gain scheduling. Performance can be improved by switching in a new controller for each plant condition. Thus, "almost" optimal control can be achieved for, say, ten linearized regions of elbow joint angle and ten regions of payload mass. One problem with this technique is to assure smooth switching between the controllers. Successful work on this important problem has been carried out on the flexible arm with optical and touch sensing. Another problem is that memory requirements grow exponentially with increasing parameters, and thus gain scheduling may not be acceptable for complex multi-link systems.

4) Inertial decoupling of linkages. One technique for reducing controller complexity is to compute in real time the known plant nonlinearities and "subtract" them from the measured plant dynamics. This gives the controller the appearance of constant inertia at each joint and thus constant gain controllers can be used. Unknown payload mass must be handled by other methods.

5) Model Reference Adaptive System (MRAS) control. Some promising techniques of applying MRAS to real time digital control of manipulators have appeared in recent literature (for example, Ref. Tomizuka, U.C. Berkeley). Unfortunately, these techniques as developed continually estimate all the parameters in the system, require excessive computation, and have unknown convergence times. A modified digital MRAS that adapts a few parameters and can be proved to have a specified convergence time might be helpful, if such could be developed.

6) Mixture of above techniques. The best control system will probably prove to be a mixture of the above techniques, such as the use of gain scheduling or inertial decoupling to compensate for known system nonlinearities and MRAS control for adaption of truly unknown parameters such as payload mass. In addition to being crucial for really good control of multi-link robot manipulator systems, this area is one of the richest in the basic science of automatic control.

A central feature with any of the control schemes, when target rendezvous is involved, will be the judicious use of feedforward strategies to quicken robot motion and maximize precision. We have therefore undertaken a special study of this problem, which is reported on in the next section.

c. Control Strategy for Moving-Target Capture Using a Two-Link Mechancial Arm

A target-tracking controller design problem for a two-link mechanical arm has been developed to assess quantitatively the capacity of feedforward to provide a quicker, more accurate tracking response over wide ranges of uncertainty or variability in the dynamic parameters of both plant and target.

Using recent developments in the theory of quadratic synthesis of robust, low-order "optimal" controllers, control logic has been developed — both with and without feedforward — that enables the arm end point to track a physical target characterized in part by periodic motion of variable or uncertain frequency and phase.

We have shown that, using relatively noise-free measurements of target position coordinates only, feedforward compensation can be expected to provide substantial reductions in tracking errors for given constraints on control effort, particularly when the range of variation in target frequency is large. As noise levels in the position measurements increase, the relative improvement in tracking accuracy (for a given level of control effort) offered by feedforward of position only decreases quite rapidly. However, if target velocity is also measured and used in the feedforward control scheme, the improvement is shown to be definitely significant even for fairly high noise levels in all target measurements.

System Configuration and Task Definition

The Stanford mechanical arm of Fig. 3-3 provided the framework for this study which is reported in detail in Ref. 3-8. Figure 3-4 depicts the target-tracking application considered for the two-link arm. Here it is desired for the arm tip to track and rendezvous with an object (target) swinging below a conveyor belt moving at constant velocity $v_{R_o} =$ 2 cm/sec. The object may have recently passed through a paint-spray booth, for example, and, upon exit, continues to have natural, undamped oscillatory motion superimposed upon the rectilinear belt motion $y_R(t)$ at constant velocity v_{R_o}.

The horizontal-plane trajectory of the target motion is approximated by an ellipse. The goal is to cause the arm tip to slew quickly to within, say, 1 cm. of the target and maintain that proximity for all times after 10 seconds. At any time thereafter a gripping mechanism can then "reach up" and grasp the target object with low relative impact velocity for subsequent transfer to the next designated point in the assembly area. Such a control sequence would be repeated continuously throughout the daily operational hours of the assembly line.

Without resorting to adaptive control schemes, it was desired to determine a robust constant-gain control strategy that would satisfy the above error requirements despite uncertainties of up to ±50% in both M_{tip} and ω_T. In addition, the torque motor peak (rms continuous) limits of 15N-m (3N-m) were not to be violated.

Figure 3-5 shows the general structure of the controller proposed for meeting the above criteria. Note that feedforward compensation appears in tandem with output error feedback compensation (including integral control) and plant inner loop (e.g. rate) feedback in the overall control scheme. At the cost of requiring one or more additional sensors,

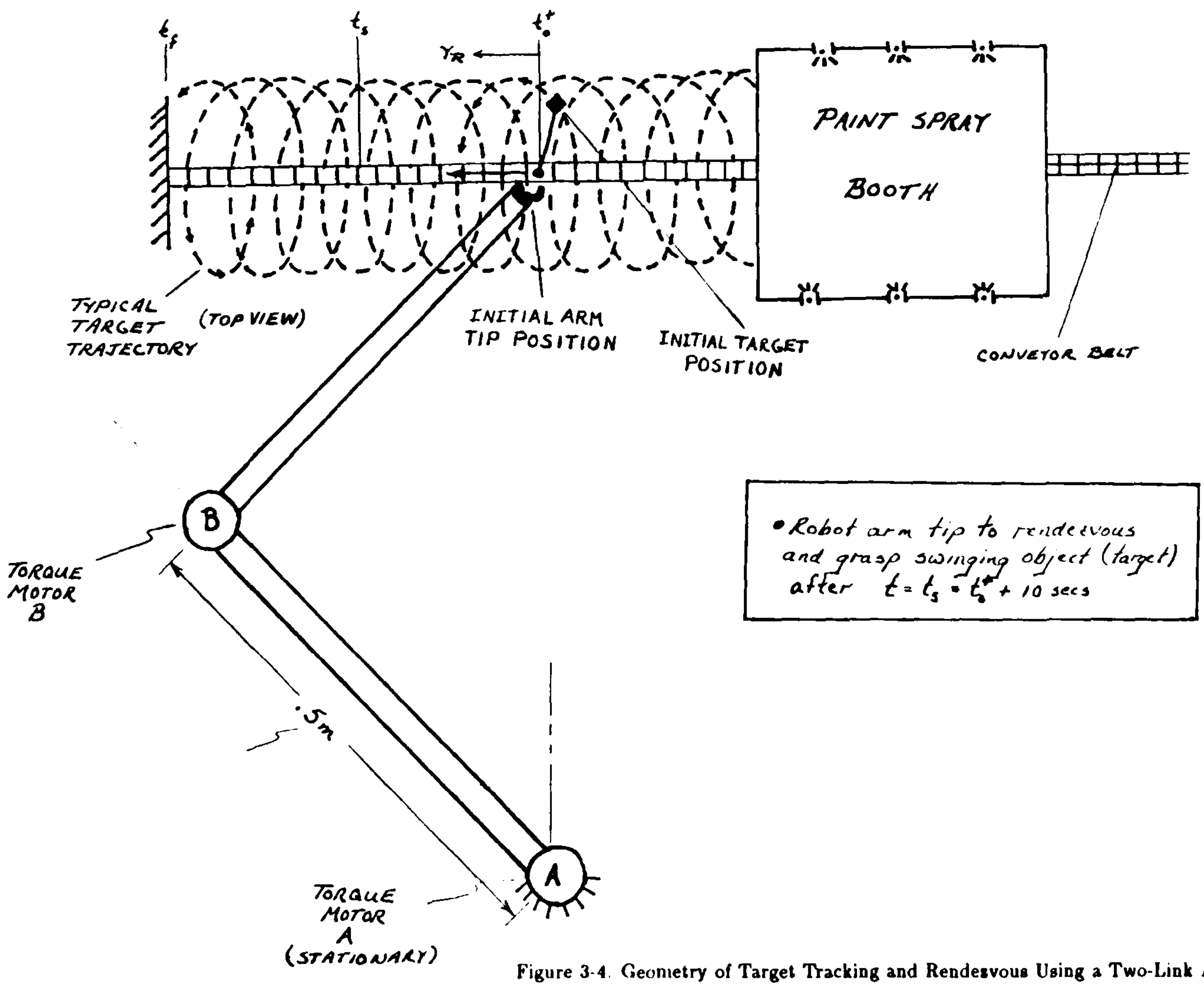
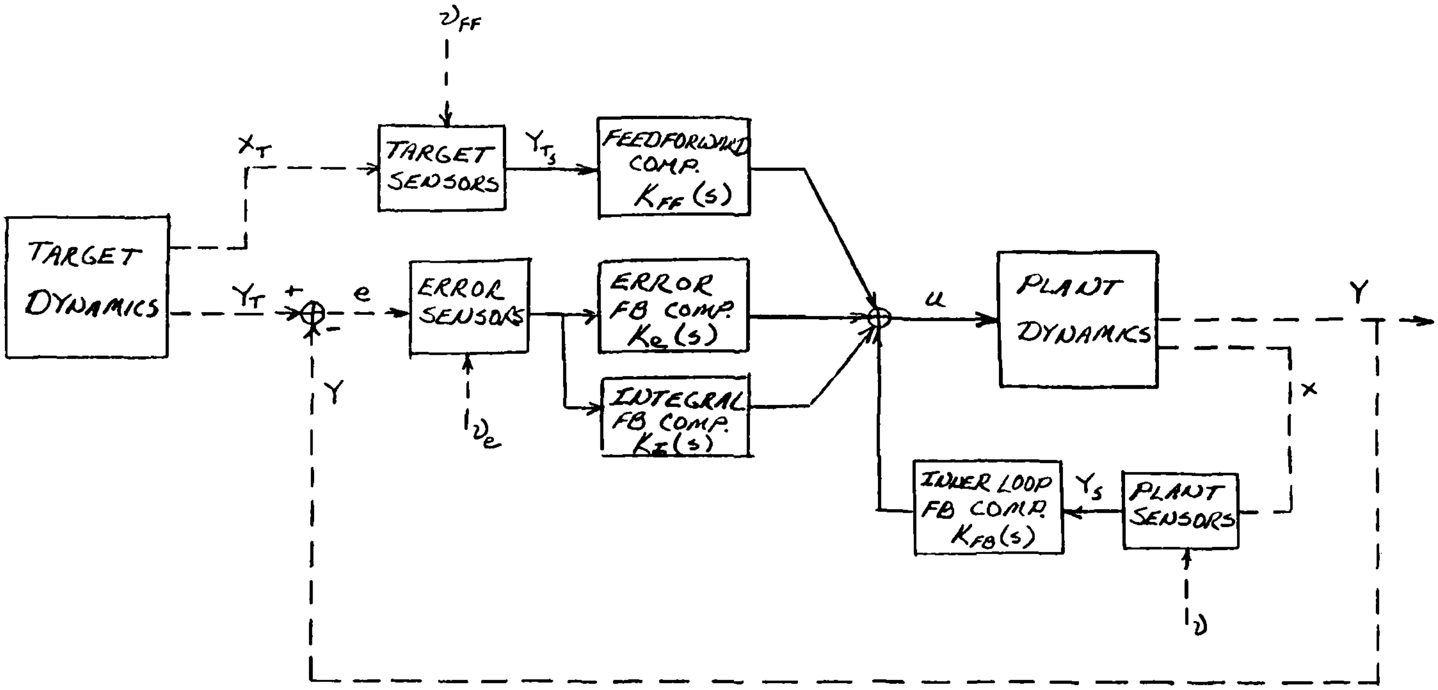


Figure 3-4. Geometry of Target Tracking and Rendesvous Using a Two-Link Arm.



$x \equiv$ Plant State vector

$Y \equiv$ Plant Output vector

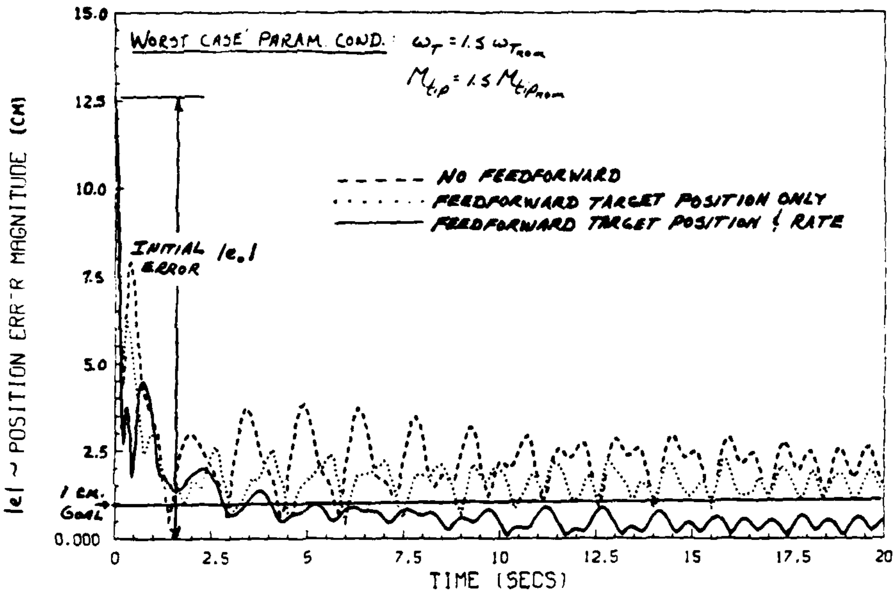
$x_T \equiv$ Target State vector

$Y_T \equiv$ Target Output vector

$e \equiv$ Error Vector

Figure 3-5. Control Scheme for Tracking a Swinging Target with a Two-Link Arm.

(a) Rendezvous Performance (Target Swinging at "Most Difficult" Frequency ω_T).



(b) Robustness of Control: Effect of Frequency of Swinging Target on Tracking Performance.

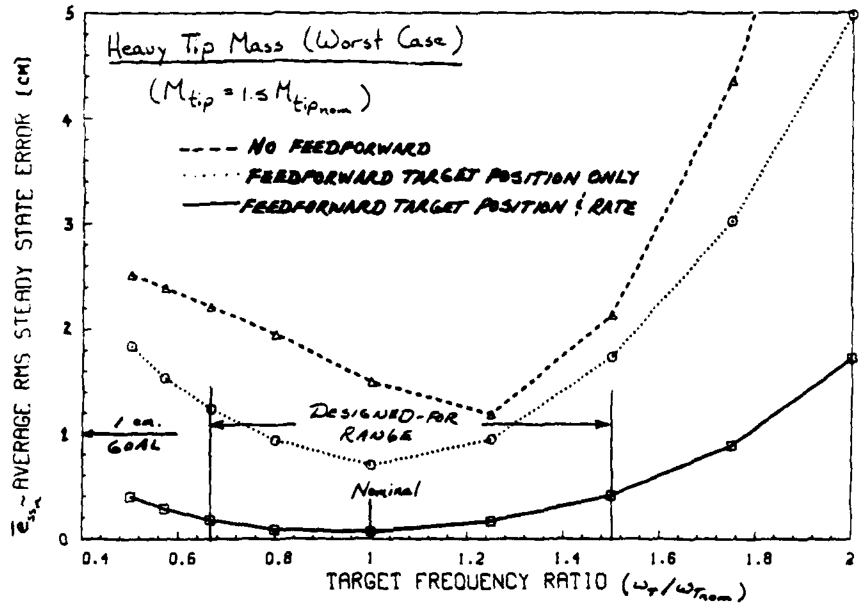


Figure 3-6. Simulation of Tracking-and-Rendezvous Performance of Proposed Feedforward/Feedback Control System for Robot of Figure 3-4.

feedforward allows for the reduction of transient tracking errors by providing the controller with early (e.g. rate) information about the future target trajectory. In addition, when the target motion is oscillatory with uncertain or variable frequency, feedforward can improve significantly the (sinusoidal) steady state error.

Results

Using alogrithms developed recently at Stanford for optimal design of robust, target-tracking controllers (Ref.3-9) control logic was synthesized for three controller structures (each a "subset" of Figure 3-5):

(I) NoFF: A controller structure with no feedforward, using error and integral error feedback in addition to feedback of arm angle rates.

(II) FF1: Same as (I), plus feedforward (with compensation) of noise-contaminated target position coordinate measurements.

(III) FF2: Same as (I), plus feedforward (with compensation) of noise-contaminated target position and rate coordinate measurements.

Each structure was designed in such a way as to optimize tracking accuracy while meeting the constraints on control effort mentioned previously.

Figure 3-6(a) shows position-error-magnitude time histories (obtained by digital simulation) for the three optimized controllers at the "worst case" parameter condition (i.e. $M_{tip} = 1.5M_{tip_{nom}}; \omega_{T_{nom}}$). Here, position-error-magnitude refers to the horizontal plane distance $| e |$ between the target and the arm tip at any time t...see Figure 3-4. It is apparent that, for the same constraints on control effort, the FF2 controller is the only one that meets the design goals, with $| e |$ settling to 1 cm. after only 5 seconds, and apparently reaching a maximum steady-state amplitude of about 0.7 cm. (i.e. 7% of average target oscillatory amplitude). This represents a reduction in steady-state error of 75% relative to the NoFF controller. The improvement obtained using feedforward of only target position coordinates (FF1) is seen to reduce the steady-state error by only 25% relative to NoFF, and fails to meet the design goal of 1 cm. or less.

Figure 3-6(b) confirms the trends observed in Figure 3-6(a) for the worst case condition: over the entire designed-for range of target frequency variability, and assuming the heavy tip mass case, Figure 3-6(b) shows that the FF2 controller easily met the design goal of 1 cm. or less steady-state error. By contrast, the FF1 controller failed to meet the design goal except in the middle portion of the designed-for range, while the NoFF controller fails over the entire designed-for range.

The results obtained indicate that the FF2 controller, using feedforward of both target position and rate coordinates, should be implemented in order to successfully meet the established design objectives.

Planned Experiments

Experiments to verify the above predicted results are planned to be carried out on the Two-Link Arm Facility.

Technical Report on Task 4

INTEGRATED TACTILE SENSORS

Overview

A touch sensory system for robotics applications is under development. Spatial information is to be generated by an array of capacitive pressure sensors, data from which are to be multiplexed together for transmission to a remote site for further signal processing. Mechanical and electrical specifications for a touch sensor were provided. Electrically, a bandwidth of 1 - 500 Hz and a response time of less than 0.1 sec. were stipulated. A low-noise data format immune to electromagnetic interference with 10-bit quantization accuracy was required. Mechanically, a touch sensor should provide a spatial resolution of less than 2 mm. and be reliable, easy to repair, self-protecting against overload, and use few wires.

In developing such a touch sensor, sub-projects include: a) an electromechanical silicon transducer; b) an integrated circuit for signal processing at the site of data collection; c) merger of the electromechanical transducer and the on-site processing circuitry into an hermetically packaged integrated silicon sensor; d) an integrated circuit for multiplexing signals from an array of such integrated sensors; and e) incorporation of the integrated array into robotic skin.

During this first year, effort has focused on the development of the required integrated sensors and circuits.

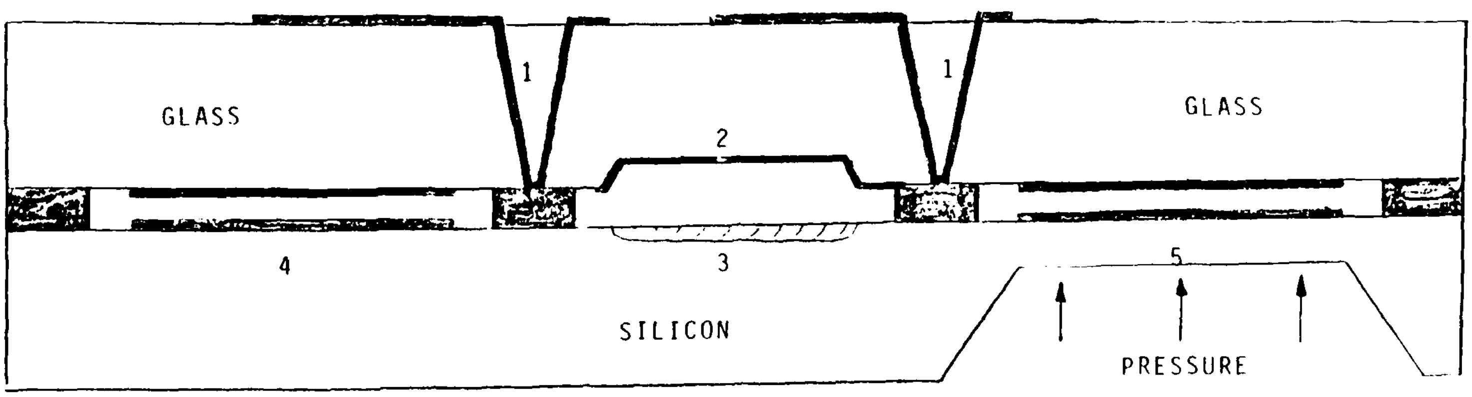
a. Transducer Micromachining

Figure 4-1 shows the structure of a single integrated capacitive pressure sensor. (This is a repeat of Fig. 1-7.) A capacitor was chosen as the transduction element due to its superior sensitivity over piezoresistive pressure sensors. Special micromachining techniques are needed for forming this structure, including chemical etching, laser drilling and welding, micro-sandblasting, and electrostatic bonding. During the past year, an automated laser workstation for micromachining glass wafers has been developed and used to produce arrays of electrical vias for electrical connection between cables attached to the top of the glass cap and the integrated circuit under the glass cap. In addition, a set of photomasks for a Mechanical Test Chip (MTCHIP) has been laid out.

Laser Workstation

The automated carbon dioxide laser workstation consists of a Cromemco Z-2D computer system, a 20 Watt Laakman Electro-Optics carbon dixide laser, a Velmex/Slo-Syn XY-table, and special purpose circuitry, jigs, and shielding. The 5 micron resolution of the XY-table and 50 micron spot size of the carbon dioxide laser allow the workstation to produce patterns of features on glass wafers which can be mated to integrated circuit patterns on silicon wafers.

A RATFOR program has been written to control the workstation. At present, only holes are implemented by the program and other features will be included in the near future. Patterns of holes in 300 micron thick pyrex wafers have been produced. These



1. electrical contact vias
2. electrostatic shield
3. custom integrated circuit
4. reference capacitor
5. pressure sensing capacitor

Figure 4-1. Integrated Pressure Sensor Cross Section.

holes are funnel-shaped; they are 120 microns in diameter on the beam entry side and 50 microns in diameter on the beam exit side of the wafer. These holes are intended to be aligned with electrical contact pads on integrated circuited in a silicon wafer to which the pyrex wafer is electrostatically bonded. The metalization of these vias is under test at present.

Mechanical Test Chip (MTCHIP)

A Mechanical Test Chip has been designed and laid out for the preparation of photomasks. MTCHIP will be used to test etching techniques for the pressure sensitive silicon diaphragm, sand-blasting and laser micromachining of the glass wafer, electrostatic bonding of the glass and silicon wafers, and cable connection to the device. The layout of photomasks for MTCHIP appear in Figure 4-2. Overall dimension of a single device are approximately 2 mm x 6 mm x 0.5 mm.

b. On Board Signal Processing

A block diagram of the signal processing and output format required for the integrated capacitive pressure sensor is shown in Figure 4-3. The current-controlled oscillator (CCO) drives logic which switches the oscillator between reference and pressure sensitive capacitors. The logic also switches the oscillator current derived from the band-gap reference, changing oscillator frequency according to the equations in Figure 4-4. Note that in addition to the sensed pressure, the circuit also produces temperature, pressure scale, temperature scale, and zero reference data. These signals are multiplexed together onto a single output line. A second output line sends a synchro nication signal for the use of other signal processing circuitry such as multiplexers and demodulators.

The temperature, scale, and reference signals provide all the information required for subsequent signal processing circuitry to calculate capacitance, and thus pressure, independent of temperature, and drifts in offset or gain. The pulse-period modulation of the output signal maximizes its immunity to noise, electromagnetic interference, and any progressive shunting of the output which may occur. Multiplexing these signals onto a single output line reduces the number of wires requried by each sensor to 4.

This circuit has been designed, simulated, breadboarded, laid out, fabricated, and tested. A photomicrograph of the circuit appears in Figure 4-5. (Same as Fig. 1-8). The circuit is fully functional but more sensitive to temperature and supply voltage than desired.

Several examples of the variation in oscillator period with changes in capacitance are shown in Figure 4-6. Variations between devices are due to shortcomings in the present fabrication process. Since clock speed in subsequent signal processing is not a limiting factor, dynamic range is determined by oscillator jitter which was measured to be 250 ppm corresponding to a dynamic range of 4000. Temperature and supply voltage coefficients are as large as 5000 ppm, however. These errors result in a temperature coefficient of 0.5 mm Hg/deg C and a supply sensitivity of 0.3 mm Hg/volt. Therefore, the circuit and its fabrication process will be refined to reduce these dependencies and fabrication variations.

c. Array Multiplexer

In application such as this, which require many sensors, it is impractical to connect wires to each sensor individually. A significant simplification in wiring results if the sensor output signals are multiplexed in time. A multisensor Controller/Multiplexer (MC/M) integrated circuit that allows the output terminals from many silicon sensors to be fused together is currently under development. This integrated circuit will fulfill a variety of specifications.

The following list is a summary of the features of the MC/M integrated circuit:.

- multiplexing rate is set by the sensors since circuitry is self clocking
- optional low-bandwidth mode for ZERO and CAL signal information
- high-bandwidth mode for accurate determination of pulse widths
- any form of pulse modulation (digital or analog) can be used in the sensors
- handshaking is available to handle uniform sampling of the sensors as well as free-running operation
- inactive sensors are detected and ignored
- sensors can be pulse-powered for reduced average system power consumption
- output signal is easily demodulated
- system start-up is assured

This integrated circuit is presently in its circuit design stage.

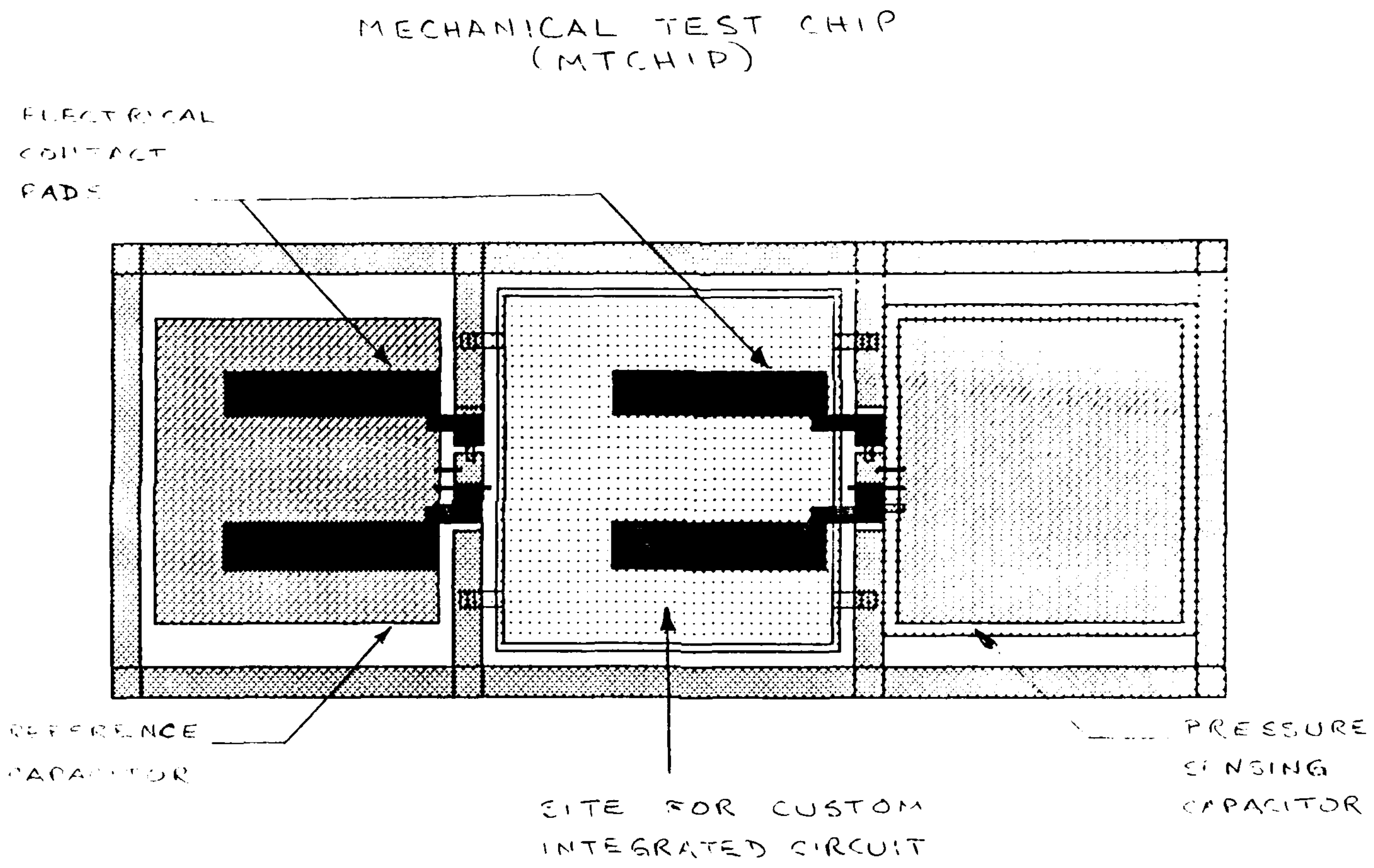


Figure 4-2. Layout of Mechanical Test Chip.

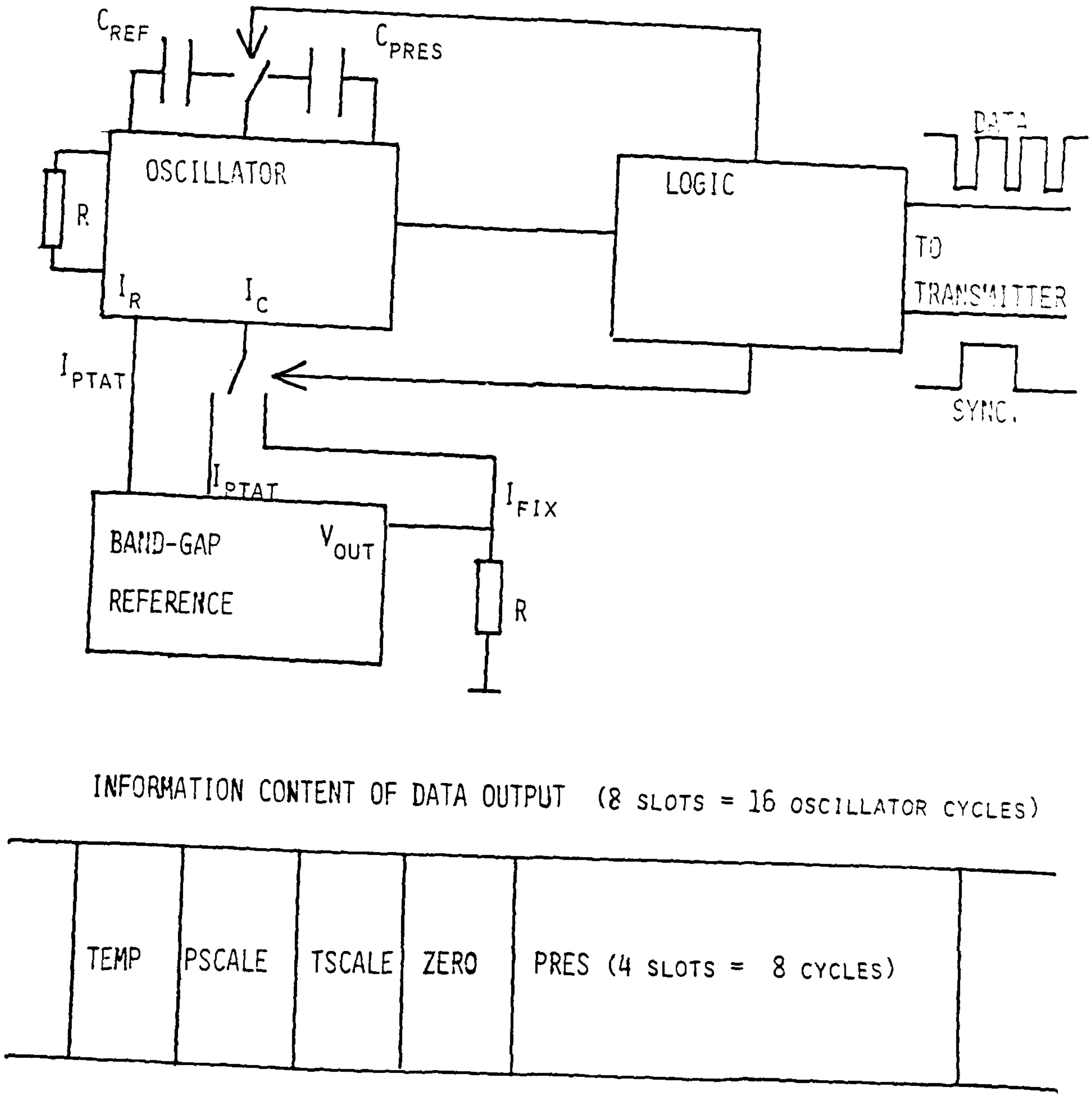


Figure 4-3. Signal Processing Block Diagram and Output Format for Integrated Capacitive Pressure Sensor.

SIGNALS SENT OUT TO MEASURE PRESSURE,

ZERO	$T = C_{REF}R + T_0$	$I_C = I_{PTAT}$
PRES	$T = C_{PRES}R + T_0$	$I_C = I_{PTAT}$
PSCALE	$T = 2C_{REF}R + T_0$	$I_C = I_{PTAT}/2$

$$\text{OSCILLATOR PERIOD}, T = \frac{CR\, I_{PTAT}}{I_C} + T_0$$

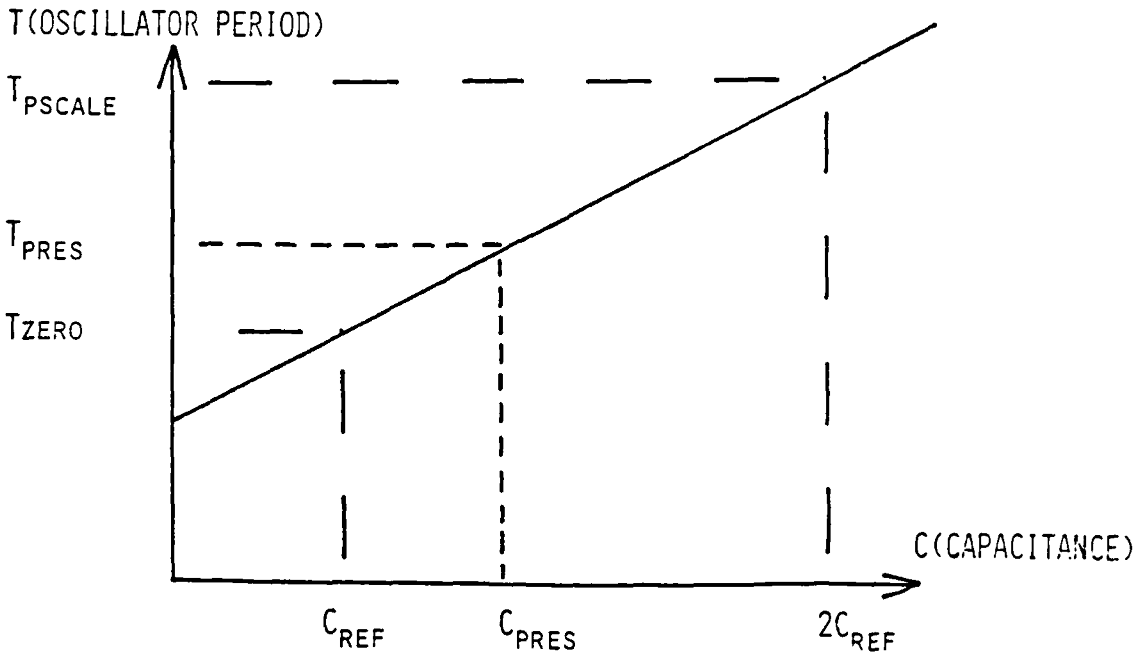


Figure 4-4. Input-Pressure/Output-Frequency Relations for Integrated Capacitive Pressure Sensor.

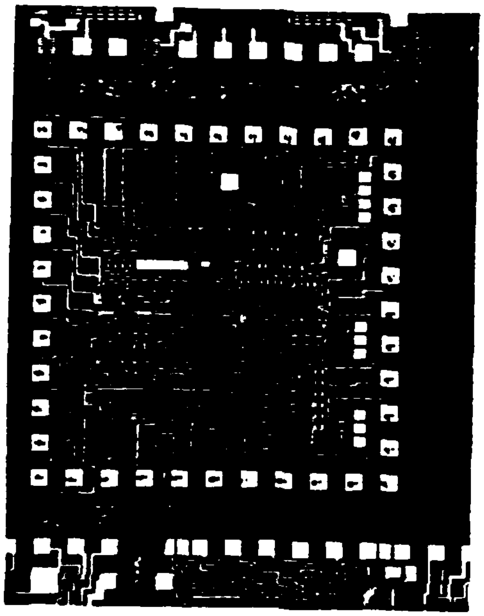
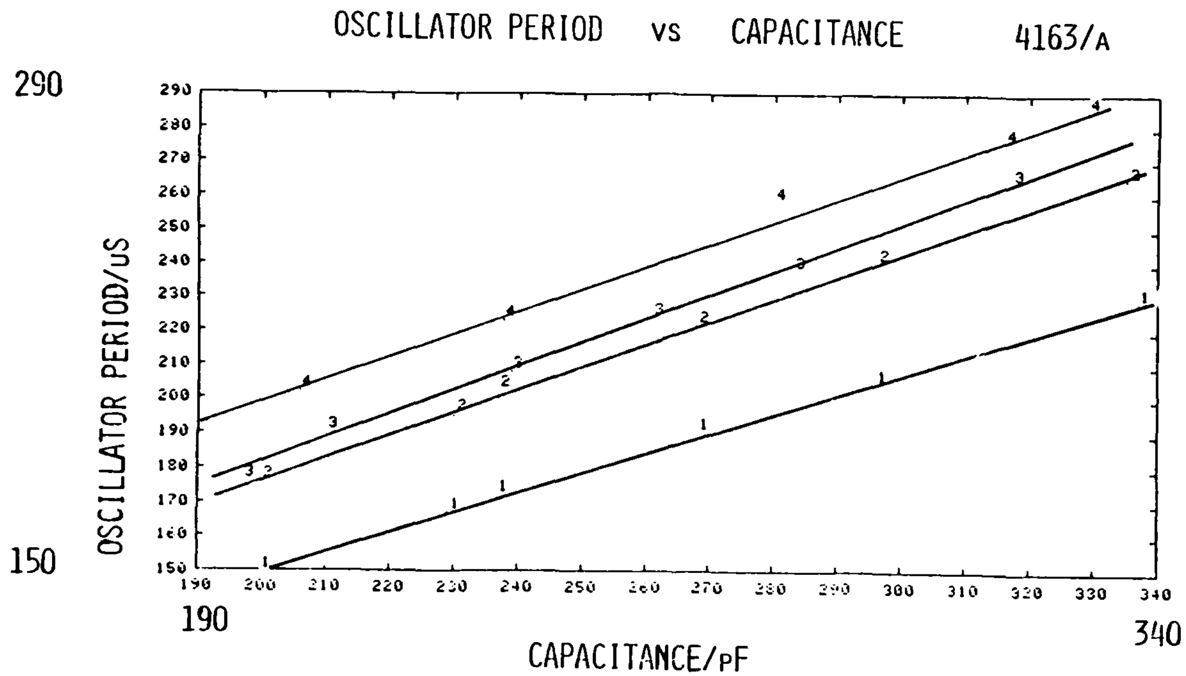


Figure 4-5. Capacitive Pressure Sensor Integrated Circuit.



T(1) = 36 + .57C

T(2) = 43 + .67C

T(3) = 42 + .70C

T(4) = 57 + .70C

Figure 4-6. Measured Performance of Several Fabricated Integrated Capacitive Pressure Sensors.

APPENDIX A

Task 2:

Publications

Ref. 2-1. Oussama, K., "Real-Time Obstacle Avoidance", (in preparation).

Ref. 2-2. Hake, J., "Joint Torque Sensing for the PUMA", (internal report).

Ref. 2-3. Binford, T., "Stereo Vision: Complexity and Constraints", Proc. Int. Symposium of Robotics Research.

Ref. 2-4. Goering, H.D., "Assembly of an Electric Motor", (internal report).

Ref. 2-5. Kirson, Y.D., Patent. Touch Sensor.

Presentations

SRI Affiliates Meeting; 3 hour presentation of entire program of the Robotics Laboratory of the Stanford Artificial Intelligence Laboratory.

AF-DARPA Workshop, March 1983, Denver. AFOSR Center of Excellence Program, Intelligent Task Automation Program.

Tri-Services Workshop on Manufacturing, June 1983. ARP Sponsor: Xerox Int. Center. The Center of Excellence and Intelligent Task Automation programs.

International Symposium of Robotics Research, August 1983, Bretton Woods, NH. Intelligent Stereo System.

Task 3:

Publications

Ref. 3-1. Gevarter, W.B., "Attitude Control of a Flexible, Spinning, Toroidal Manned Space Station," Ph.D. Thesis, Aeronautics and Astronautics Department, Stanford University, November 1965.

Ref. 3-2. Ly, U., "A Design Algorithm for Robust, Low-Order Controllers," Stanford University, SUDAAR 536, November 1982.

Ref. 3-3. Ly, U. and Cannon, R.H., "Design of Low-Order Compensators Using Parameter Optimization," To appear in Automatica, The Journal of the International Federation of Automatic Control.

Ref. 3-4. Rosenthal D. and Cannon, R.H., "Experiments with Noncolocated Control of Flexible Structures," presented at the AIAA Conference, Albuquerque, New Mexico, August 19-21, 1981.

Ref. 3-5. Schmitz E. and Cannon, R.H., "Control of a Flexible Manipulator Link," Proc. 1981 Joint Automatic Control Conference, Charlotsville, Virginia, June 17-19, 1981.

Ref. 3-6. Schmitz E. and Cannon, R.H., "Initial Experiments on the End-Point Control of a Flexible One Link Robot," To appear in the International Journal of Robotics Research.

Ref. 3-8. Gardner, B "Robust Feedforward/Feedback Control Logic for a Target-Tracking Mechanical Arm," Stanford University, SUDAAR 537, December 1983.

In Preparation

Hollars, M., "End-Point Control of Manipulator with Flexible Tendon Drives: Experimental Results" To be presented at the Society for Manufacturing Engineering Robot 8 Conference at Detroit in June, 1984.

Gardner, Bruce., "Feedforward/Feedback Control Logic for Robust Target-Tracking" Ph.D Thesis, Stanford University.

Presentations

1) Special DARPA-AFOSR Conference on Programs in Automation, March, 1983, Denver.

2) Keynote Speech, "Automatic Control of Robots," American Control Conferernce, San Francisco, June, 1983.

3) Int Symp of Robotics Research, August 1983, Bretton Woods, NH. Special Keynote Address:

4) DARPA Workshop on Mechanical Innovations in Robotics, "Initial Experiments on the End-Point Control of a Flexible One Link Robot", Menlo Park, October, 1983.

APPENDIX B

PEOPLE

Principal Investigators:
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Cregg Cowan
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ROBERT H. CANNON, JR.

Charles Lee Powell Professor and Chairman

Department of Aeronautics and Astronautics

Stanford University

Education:

B.S. University of Rochester, 1944

Sc.D. Massachusetts Institute of Technology, 1950

Experience:

1979 -	Charles Lee Powell Professor and Chairman, Department of Aeronautics and Astronautics, Stanford University.
1974 - 1979	Professor of Engineering and Chairman, Division of Engineering and Applied Science, California Institute of Technology.
1980 -	Chairman, General Motors Science Advisory Committee. Member since 1975)
1979 -	Director, Parker Hannifin Corporation.
1975 - 1979	Director, Bertea Corporation.
1970 - 1974	U.S. Assistant Secretary of Transportation.
1966 - 1968	Chief Scientist, U.S. Air Force.

1959 - 1970	Professor and Vice Chairman, Department of Aeronautics and Astronautics and Director of the Guidance and Control Laboratory, Stanford University.
1957 - 1959	Associate Professor of Mechanical Engineering, Massachusetts Institute of Technology.
1951 - 1957	Supervisor, research and development in flight control and inertial navigation systems, Autonetics Division of North American Aviation, Downey, California.
1950 - 1951	Research Engineer, Bendix Aviation Research Laboratories, Detroit, Michigan.

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Professional Memberships:

National Academy of Engineering

Fellow, American Institute of Aeronautics and Astronautics

Tau Beta Pi

Sigma Xi

Honors and Awards:

Outstanding Achievement Award, U.S. Department of Transportation 1974

Exceptional Civilian Service Award, U.S. Air Force 1969

Public Service:

Chairman, Assembly of Engineering, National Research Council (1974-75).

Council Member, National Academy of Engineering (1975-81).

Member, National Research Council Governing Board (1975-78).

Chairman, Energy Engineering Board, National Research Council (1975-1981).

Member, NRC Committee on Nuclear and Alternative Energy Sources (1975-78).

Member, NRC Aeronautics and Space Engineering Board (1975-78).

Chairman, NASA Research Advisory Subcommittee on Guidance, Control and Navigation (1968-70).

Chairman, NASA Electronics Research Center Advisory Group (1968-70).

Vice Chairman, U.S. Air Force Scientific Advisory Board (1968-70).

Director, American Institute of Aeronautics and Astronautics (1968-70).

Chairman, AIAA Technical Committee on Guidance and Control (1964-66).

Member, AGARD (NATO) Guidance and Control Panel (1968).

Member, Advisory Committee, Air Force Institute of Technology (1969)

Advisor, USAF Space and Missile Systems Organization Advisory Group (1969)

Some Technical Contributions:

Helped develop several successful passenger-carrying hydrofoil boats, including 21 knot sailboat ('46-'47), contributed to early electronic analog computer development ('48-'50); analytical design and test of E-7 automatic flight control system ('51-'54), autopilot design for POGO VTOL ('52); contributed to gyro and stable platform development for Navaho and Minuteman missiles, Nautilus and Skate submarines (first polar journeys) ('54-'57); established Stanford University program in guidance and control, where (among others) projects to provide drag-free control (to within $10^{-12}g$) for the Transit satellite, and to bench test accelerometers in 10^{-5} to $10^{-12}g$ range have been completed, ('59-'72); and engineering for a gyro test of General Relativity in a satelite (accuracy ≈ .001 sec per year) is in progress. Initiated Air Force space precision attitude reference system (SPARS) project and several others (1968). Helped lead major National Academy study of U.S. energy needs, opportunities, and alternatives (1975-78). Developed (with William McLain) and lab tested a model wave actuated upwelling pump (Scripps hydrodynamic wavetank)(1976-78). Early fundamental work on direct design of robust control systems (1975-78). Precision control of very flexible manipulators for robots and spacecraft, using (noncolocated) end-point sensing (1979-).

Some Nontechnical Contributions:

Structured the R and D management of the U.S. Department of Transportation. Established the position of Chief Scientist. Established the DOT Program of University Research. Established the DOT R and D Policy Office.

Responsible for shepherding the DOT Transportation Systems Center (in Cambridge) into being, structuring its mission, getting its programs supported and getting a major program in socio-economic research established there.

Contributed stimulus and helped garner support for the national air traffic control system (ARTS III and Fourth Generation) now coming on line.

Originated and responsible for major technology assessment on the environmental impact of stratospheric flight.

Patents:

Load Factor Cut-Out Switch for Aircraft Autopilots (No. 2929260) — A failure detection and safety device usable with any autopilot. An all-mechanical sensor and switch determines independently when aircraft motions, if continued, could result in exceeding safe load factor, and automatically turns off autopilot before they do (8 16 60).

Gust Alleviation System (No. 2985409) — Reduces gust response of any appropriately equipped aircraft. Using signals from properly placed accelerometer and gyro, computer predicts gust loading to come and moves control surfaces to produce countering force so that net force, and therefore aircraft motion, are small (5 23 61).

ROBERT H. CANNON, JR.

Selected Publications:

1. Textbook: *Dynamics of Physical Systems,* McGraw-Hill, 1968, 925 pp.
2. "Performance of Hydrofoil Systems," Sc.D. Thesis, MIT, June 1950.
3. "Automatic Control of High-Performance Aircraft," *J. Inst. Nav.,* Vol. 4, No. 5, March 1955.
4. "Stable Platforms for High-Performance Aircraft," (with D.P. Chandler), *Aero. Engr. Rev.,* Vol. 16, No. 12, December 1957.
5. "Rectification Drift in Single-Axis Gyroscopes," *J. of Appl. Mech.,* Vol. 25, No. 3, September 1958, p. 357.
6. "Root Locus Analysis of Structural Coupling in Control Systems," *J. of Appl. Mech.,* Vol. 26, No. 2, June 1959, p. 205.
7. Articles on Guidance Systems, Inertial Guidance, Navigation, Control, Missile Guidance, Fire Control System, Autopilots, Navigation Instruments, Gyrocompass, Gyroscope, and Schuler Pendulum contributed to *Encyclopedia of Science and Technology,* McGraw-Hill, 1960.
8. "Vibration Analysis by the Root Locus Method," *Proceedings Third U.S. National Congress of Applied Mechanics.*
9. "Gyrocompass Alignment of Inertial Guidance Systems," *J. Aerospace Sciences,* Vol. 28, No. 11, November 1961.
10. "Gyroscopic Coupling in Space Vehicle Attitude Control Systems," *ASME J. of Basic Engr.,* Vol. 84. Series D. No. 1, March 1962.
11. "Momentum Vector Considerations in Wheel-Jet Satellite Control System Design" (with D.B. DeBra), *Progress in Astronautics and Rocketry,* Vol. 8 (Roberson and Farrior, eds.) Academic Press, 1962.
12. "Some Basic Response Relations for Reaction-Wheel Attitude Control Systems," *ARS J.,* Vol. 32, No. 1, January 1962.
13. "Requirements and Design for a Special Gyro for Measuring General Relativity Effects," Kreiselproblema (H. Ziegler, ed.), Springer Verlag, Berlin, 1963, pp. 146-160.
14. "Basic Response Relations for Attitude Control Systems Using Gyros," presented at International Federation of Automatic Control, Basel, Switzerland, 1963, *Proc. IFAC,* 1963, Butterworths.
15. "The Vector Reticle and Control Action Display in Manual Control of Space Vehicle Attitude" (with Walter G. Eppler, Jr.), *J. of Spacecraft and Rockets,* February-March 1965.
16. "On the Control of Unstable Mechanical Systems" (with John F. Schaefer), presented at the International Federation of Automatic Control, London, England, 1966, *Proc.*

IFAC, 1966, Butterworths.

17. "Flotation Technique for Laboratory Calibration of Low-Level Accelerometers" (with B.K. Likeness), *J. of Spacecraft and Rockets,* Vol. 6, September 1969, pp. 991-997.

18. "Planning a Program for Assessing the Possibility that SST Aircraft Might Modify Climate," *Bull. of the American Meteorological Soc.,* Vol. 52, No. 9, September 1971, pp. 836-842.

19. "Transportation, Automation, and Societal Structure," *Proceedings of the IEEE,* Vol. 61, No. 5, May 1973, pp. 518-525.

20. "The Effects of Stratospheric Pollution by Aircraft" (with A.J. Grobecker and S.C. Coroniti), *Report of Findings, U.S. Department of Transportation, Climatic Impact Assessment Program* (DOT-TST-75-50), Washington, D.C., March 1975, 851 pp.

21. Vinkler, A., Wood,L., Ly, U., Cannon, R.H. "Minimum Expected Cost Control of a Remotely Piloted Vehicle," *Journal of Guidance and Control,* Vol. 3, No. 6, November-December 1980.

22. "Energy in Transition 1985-2010," Final Report of the Committee on Nuclear and Alternative Energy Systems, National Research Council, National Academy of Sciences, Washington, DC, 1979.

23. Schmitz, E. and Cannon, R.H., "Control of a Flexible Manipulator Link," presented at the 1981 Joint Automatic Control Conference, Charlottesville, Virginia, June 17-19, 1981.

24. Rosenthal, D. and Cannon, R.H., "Experiments with Noncolocated Control of Flexible Structures," presented at the AIAA Conference, Albuquerque, New Mexico, August 19-21, 1981.

25. Cannon, R.H., and Schmitz, E., "Initial Experiments on the End-Point Control of a Flexible One Link Robot," Submitted to the Journal of Robotics, December, 1983.

26. Cannon, R.H., and Rosenthal, D., "Experiments with Noncolocated Control of Flexible Structures," Submitted to Journal of Guidance and Control, December, 1983.

Curriculum Vitae

Thomas O. Binford

US Citizen

Stanford University

Professor, Computer Science Dept (1970 -)

Leader of Computer Vision and Robotics group at the Stanford Artificial Intelligence Laboratory.

Massachusetts Institute of Technology

Research Associate, Artificial Intelligence Laboratory (1967-1970). Research Topics: artificial intelligence, computer vision, representation of shape, LISP programming systems.

Fulbright Fellowship, Tata Institute of Fundamental Research, Bombay, India (1965-1966) Research topic: experimental elementary particle physics; partial wave analysis of hyperon production by pions; Regge-pole analysis of elastic scattering; theory of unstable particles and symmetry principles.

Education

PhD in Physics, the University of Wisconsin, 1965. BS in physics, Pennsylvania State University, 1957.

Bibliography

T.O. Binford; *"Stereo Vision:Complexity and Constraints"*; Proc. First International Symposium of Robotics Research, Bretton Woods N.H. Sept. 1983.

T.O. Binford; *"Intelligent Vision Systems"*; Proc. IU Workshop Image Understanding May 1983.

T.O. Binford; *"Computer Integrated Assembly Systems"*; National Science Foundation, 1983.

Patrick H. Winston:T.O. Binford; Katz, Boris T.; Lowry, Michael; *Learning Physical Descriptions from Functional Definitions, Examples and Precedents* Stanford University AIM-349 report#STAN-CS-82-950 1983, MIT Memo 679.

D. Lowe, T.O. Binford; *Perceptual Organization as a Basis for Visual Recognition"*; Proc IU Workshop, May 1983.

Baker, H.Harlyn; T.O. Binford; Malik, Jitendra; Meller, Jean-Frederic; *"Progress in Stereo Mapping"*; Proc IU Wkshp May 1983.

D.Lowe; T.O. Binford; *"Perceptual Organization as a Basis for Visual Recognition"*; Proc AAAI, August 1983.

H. Harlyn Baker; T.O. Binford; *"A System for Automated Stereo Mapping"*; Proc IU Wkshp 1982.

D.Lowe; Binford T.O.; *"Segmentation and Aggregation: An Approach to Figure-Ground Phenomena"*; Proc IU Wkshp 1982.

T.O. Binford; *"Figure/Ground: Segmentation and Aggregation"*; Rank Prize Fund Conference, England, 1982.

D. Lowe, T.O.Binford; *"Segmentation and Aggregation: Figure-Ground Phenomena"*; Proc. IU Workshop September 1982.

Malik, J.M., T.O. Binford; *"Representation of Time and Sequences of Events"*; Proc. IU Workshop Image Understanding September 1982.

T.O. Binford; *"Survey of Model-based Image Analysis Systems"*; Robotics Research Vol 1, No 1, March 1982.

T.O. Binford; *"Geometric Reasoning and Spatial Understanding"* Proc IU Wkshp 1982.

T.O.Binford; *"Computer Integrated Assembly Systems"*; Proc NSF Conference, University of Michigan, November 1981.

T.O.Binford; *"Inferring Surfaces from Images"*; Artificial Intelligence Journal, August, 1981.

D.Lowe; T.O. Binford; *"The Interpretation of Geometric Structure from Image Boundaries;"* Proc Image Understanding Workshop, April 1981.

D.Lowe; T.O. Binford; *"The Interpretation of Three-Dimensonal Structure from Image Curves"*; Proc Int Joint Conf on AI, Aug 1981.

T.O.Binford; *"Inferring Surfaces from Images"*; Artificial Intelligence Journal, July 1981.

H. Baker; T.O. Binford; *"Depth from Edge and Intensity Based Stereo"*; Proc Int Joint Conf on AI, Aug 1981.

P.J. MacVicar-Whelan, and T.O. Binford; *"Intensity Discontinuity Location to Subpixel Precision"*; Proc Int Joint Conf on AI, Aug 1981.

D.Lowe, T.O.Binford; *"The Interpretation of Three-Dimensonal Structure from Image Curves"*; Proc Int Joint Conf on AI, Aug 1981.

D.Lowe, T.O.Binford; *"The Interpretation of Geometric Structure from Image Boundaries"*; Proc Image Understanding Workshop, April 1981.

T.O.Binford, R.A.Brooks; *"Geometric Modeling in Vision for Manufacturing"*; Proc Image Understanding Workshop, April 1981.

P. MacVicar-Whelan, T.O.Binford; *"Line-finding to sub-Pixel Accuracy"*; Proc Image Understanding Workshop, April 1981.

T.O. Binford, Brooks, R.A., D. LoweG.; *"Image Understanding Via Geometric Models"*; Proc 5th Int Conf on Pattern Recognition, Miami, 1980.

R.D.Arnold, T.O.Binford: *"Geometric Constraints in Stereo Vision"* Proc. SPIE Meeting, San Diego, Cal, July 1980.

Brooks, R.A., T.O. Binford; *"Interpretive Vision and Restriction Graphs"*; Proc Am Assoc for AI Conf, Stanford 1980.

Brooks, R.A., T.O. Binford; *"Representing and Reasoning about Partially Specified Scenes"*; Proc Image Understanding Workshop, Baltimore, April 1980.

T.O.Binford; *"Computer Integrated Assembly Systems"*; Proc Seventh NSF Grantees Conf on Production Research and Technology, Cornell, 1979.

R. Brooks, R. Greiner, and T.O. Binford; *"ACRONYM: A Model-Based Vision System"*; Proc International Joint Conf on AI, Aug 1979.

T.O.Binford; *"AL, A Programming Language For Robots"*; Proc Int Seminar on Prog Lang for Robots, IRIA, Paris, 1979.

T.O. Binford, Brooks, R.; *"Geometric Reasoning in ACRONYM"*; Proc Image Understanding Workshop", Palo Alto, Calif, Apr 1979.

Brooks,R.; Greiner, R.; T.O. Binford; *"Progress Report on a Model-Based Vision System"*; Proceedings Image Understanding Workshop", Carnegie-Mellon, Nov 1978.

Brooks, R.;Greiner,R.;T.O. Binford; *"A Model-Based Vision System"*; Proceedings ARPA Image Understanding Workshop, MIT, Cambridge, Mass, May 1978.

Binford,T.O.;Lui,C.R.;Gini,G.; Gini,M.; Glaser,I.; Mujtaba,M.S.; Nakano, E.; Nabavi F.D; Panofsky,E.; Shimano,B.E.;Goldman, R.; Scheinman, V.; Schmelling,D.; Gafford,T.; *"Exploratory Study of Computer Integrated Assembly Systems, Progress Report 4"* AIM-285.4, STAN-CS-76-568, June 1977.

R. Nevatia;T.O. Binford; *"Description and Recognition of Curved Objects"*; Artificial Intelligence, Vol 8, p 77, Feb 1977;

T.O. Binford; et al, *"Exploratory Study of Computer Integrated Assembly Systems"*, Stanford Artificial Intelligence Laboratory, Memo AIM-285, Third Report, Aug 1976.

G. Agin and T.O.Binford, *"Representation and Description of Complex Objects"*, IEEE Transactions on Digital Computers, Nov 1975.

T.O.Binford,*"Computer Vision and Productivity Technology"*, Invited Tutorial, Fourth International Conference on Artificial Intelligence Tbilisi, Georgia, USSR, September 1975.

T.O.Binford et al, *"Exploratory Study of Computer Integrated Assembly Systems"*, Second Report, Stanford Artificial Intelligence Laboratory, Dec 1975.

E.Miyamoto and T.O.Binford, *"Display Generated by a Generalized Cone Representation"*, Conference on

Computer Graphics and Image Processing, May 1975.

T.O.Binford et al. *"Exploratory Study of Computer Integrated Assembly Systems"*, First Report, Stanford Artificial Intelligence Laboratory, Oct 1974.

A.J.Thomas and T.O.Binford, *"Information Processing Analysis of Visual Perception, A Review"*, Stanford Artificial Intelligence Laboratory, Memo AIM-227, June 1974.

W.A.Perkins and T.O.Binford, *"A Corner Finder for Visual Feedback"*, Computer Graphics and Image Processing 2, December 1973.

R.K.Nevatia and T.O.Binford, *"Structured Descriptions of Complex Objects"*, Third Int Conf on AI, Stanford, Calif, 1973.

G. Agin and T.O.Binford, *"Representation and Description of Complex Objects"*, Third Int Jt Conf on AI, Stanford, Calif, 1973.

T.O.Binford and J.M.Tenenbaum, *"Computer Vision"*, IEEE Computer, May 1973, 19-24.

T.O.Binford, *"Sensor Systems for Manipulation"*, Conference on Remotely Manned Systems, JPL, Pasadena, Calif, Sept 1972.

T.O.Binford, *"Visual Perception by Computer"*, Invited paper at IEEE Systems Science and Cybernetics Conf, Miami, Dec 1971.

With Feldman, et al, *"The Use of Vision and Manipulation to Solve the Instant Insanity Puzzle"*, Proc. Second International Joint Conference on Artificial Intelligence.

With Tenenbaum, et al, *"A laboratory for Hand-Eye Research"*, IFIP proceedings, August 1971.

T.O.Binford, *"The Vision Laboratory-Part One"*, MIT AI memo 203.

A. Herskovits and T.O.Binford, *"On Boundary Detection"*, MIT AI memo 183.

T.O.Binford, *"Display Functions in LISP"*, MIT AI memo 182, Jan 1970.

B.R. Desai and T.O.Binford, *"High Energy Elastic Scattering at Low Momentum Transfers"*, Physical Review 138,B1167.

With others, *"Experimental Check of Some SU(6* Cross Section Equalities"), Physical Review Letters 14,715.

Binford et al. *"Hyperon Production in Pion Interactions"*, Physical Review (1968).

With others, *"Triangle Inequality in Associated Production"*. Physical Review (1968).

With Anderson, et al, *"CP-Nonconserving three-pion Decay of Kzero"*, Physical Review Letters 14,475.

With Stern et al, *"Absolute Decay Rate for Leptonic Decays of Kzero and the Delta I = 1/2 Rule"*, Physical Review Letters 12,459.

With Lind, et al, *"Experimental Investigation of V-A in Leptonic Lambda Decay"*, Phys Rev 135,B1483.

Committees

Member NASA committee on Automation and Future Missions in Space; 1980. Member NASA committee on Machine Intelligence and Robotics, 1977-78. Associate Editor, Robotics Research Associate Editor, IEEE Proceedings on Pattern Analysis and Machine Intelligence, 1981. Associate Editor, Computer Graphics and Image Processing; 1977-81. Member IEEE Pattern Recognition Technical Committee.

Conferences and Workshops

National Academy of Sciences, July 19-20th, Washington D.C., Panel member "Computers in Design and Manufacturing.

NSF Grantees Conference on Productivity Research, Jan 1981, organizer.

Conference on Computer Vision, Pajaro Dunes, Calif, 1980, chairman.

NSF Workshop on Software for Assembly, Chicago, Illinois, Nov 1976, chairman.

Conference on Cognitive Robotics Systems, Pasadena, Calif, Mar 1975, co-chairman

NSF Workshop on Sensors for Automation, Lexington, Mass, 1973

co-chairman, industrial automation section

Conference on Computer Vision, Pajaro Dunes, Calif, 1973, chairman.

Conference on Computer Vision, Pajaro Dunes, Calif, 1972, chairman.

Conference on Computer Vision, Pajaro Dunes, Calif, 1971, chairman.

PhD Students

G.J.Agin, *"Description and Representation of Complex objects"*(1972)

R.K.Nevatia, *"Recognition of Complex Objects"(1974)*

Ruzena Bajcsy, (under Prof J. McCarthy), *"Computer Identification of Textured Visual Scenes"(1972)*

T. Garvey, *"Purposive Vision"(1975)*

D. Gennery, *"Modeling the Environment of an Exploring Vehicle by means of Stereo Vision"(1980)*

R.D. Arnold(1981)

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Education:

1977-1981 Ph.D., Computer Science Department, Stanford University, California. Dissertation title: "Symbolic Reasoning Among 3-D Models and 2-D Images".

1976-1977 M.Sc., School of Mathematical Sciences, Flinders University, South Australia. Dissertation title: "Similarity Networks".

1975 B.Sc. Hons., School of Mathematical Sciences, Flinders University, South Australia. Pure Mathematics. Awarded first class Honours.

1972-1974 B.Sc., School of Mathematical Sciences, Flinders University, South Australia. Pure Mathematics.

Awards and Honors

1982 Honorable Mention, Tioga Competition, American Association for Artificial Intelligence National Conference, Pittsburgh, Pa., August.

1975 Flinders University Medal.

1975 Australian Postgraduate Research Award.

Employment History:

1983 (Aug) present, Assistant Professor of Computer Science, Stanford University. Direct research in automated assembly, robot vision systems, mobile robots and software systems for artificial intelligence.

1981 1983 Research Scientist, Artificial Intelligence Laboratory, MIT, Cambridge, Ma. Research in geometric modelling and planning algorithms for task level manipulator programming of automatic assemblies - including research into collision avoidance algorithms and dealing with uncertain situations.

1981 (summer) Research Associate, Computer Science Department, Carnegie Mellon University, Pittsburgh, Pa. Design of "Common Lisp" and implementation of it for the S-1, mark II-A multiprocessor.

1977-1981 Research Assistant, Stanford Artificial Intelligence Laboratory. Worked with Prof. Thomas Binford on problems in geometric modelling, spatial reasoning and computer vision, culminating in the design and implementation of the ACRONYM system for model-based vision and assembly planning.

1979 (summer) Research Assistant, Stanford Artificial Intelligence Laboratory. Design and preliminary implementation of a lisp dialect for the S-1, mark II-A multiprocessor (under development at Lawrence Livermore Labs).

1976-1977 Tutor in the School of Mathematical Sciences, Flinders University.

1975-1976 Australian Development Assistance Agency. Tutor.

1973 (Christmas - southern hemisphere summer) Research Programmer, Australian Bureau of Meteorology.

Invited Talks:

16 Nov 1983. Distinguished Lecture Series. Computer Science Department, University of Wisconsin, Madison, Wisconsin.

25-27 Sept 1983. General Motors Symposium on Solid Modeling by Computers: From Theory to Applications. Warren, Michigan.

28 Aug – 2 Sept 1983. First International Symposium of Robotics Research, Bretton Woods, New Hampshire.

15 July 1983. *Model Directed Vision.* Robotics Systems Course, IBM Europe Institute 1983, Grassau, Germany.

28 June 1983. *Knowledge Base Design for Robotics.* Tutorial lecture at NASA workshop on "Autonomy and the Human Element in Space", Stanford University.

21 April 1983. *Spatial Reasoning for Mobility and Manipulation.* Army Research Office Conference on Artificial Intelligence, Silver Springs, Maryland.

14 April 1983. *Acronym: A Model-Based Approach to Image Understanding.* Army Research Office Worshop on Image Analysis, Brown University, Providence, Rhode Island.

1 March 1983. *Automatic Planning of Robot Assembly Tasks.* Lincoln Labs, Massachusetts.

8 February 1983. *Symbolic Error Analysis and Robot Planning.* Computer Science Colloquium, University of Pennsylvania, Philadelphia.

13 January 1983. *Getting from Plan Outlines to Real World Sensing and Control.* Bolt, Beranek and Newman, Cambridge Massachusetts.

14 December 1982. *Automatic Control of Sensory Data Collection through Symbolic Error Analysis.* Symposium on Automated Manufacturing and Robotics, Washington D. C. Sponsored by the National Bureau of Standards and the Office of Naval Research.

14 July 1982. *The ACRONYM Model Based Vision System.* Computer Vision Laboratory, University of Maryland.

12 July 1982. *Geometric Reasoning for Vision and Assembly.* IBM, T. J. Watson Research Center Seminar.

17 June 1982. *Representing Possible Realities for Vision and Manipulation.* IEEE Conference on Pattern Recognition and Image Processing, Las Vegas.

1 March 1982. *Model Based Vision.* Computer Science Dept. Colloquium, Yale University

Other Activities:

August 1983 – present. Consultant to MIT Lincoln Laboratories.

August 1983. Session organizer, AAAI satellite workshop on *Sensors and Algorithms for 3-D Perception*, Washington, D.C.

October 1981 – present. Member of national Common Lisp committee, developing a new standard dialect of lisp. (Chairman is Guy Steele of Carnegie Mellon University.)

October 1981 – present. Consultant to Hughes Research Laboratories, Malibu.

October 1981 – present. Consultant to Lawrence Livermore National Laboratory, Livermore, on design of a multiprocessor lisp system for their S-1 series of computers.

November 1982 and occasionally thereafter. Consultant to Teknowledge Inc., Palo Alto, California.

March 1982. Consultant to ENSCO Inc., Virginia.

February 1982. Consultant to SRI International.

Journal Articles:

1. Rodney A. Brooks, "Symbolic Reasoning Among 3-D Models and 2-D Images"; *Artificial Intelligence Journal* (17) 1981, 285-348.

2. Rodney A. Brooks, "Symbolic Error Analysis and Robot Planning"; *International Journal of Robotics Research*, vol 1, no. 4, Dec. 1982, 29-68.

3. Rodney A. Brooks, "Model-Based Three Dimensional Interpretations of Two Dimensional Images"; *IEEE Pattern Analysis and Machine Intelligence*, March 1983, 140-150.

4. Rodney A. Brooks, "Solving the Find Path Problem by Good Representation of Free Space"; *IEEE Systems, Man and Cybernetics*, SMC-13, March 1983, 190-197.

5. Rodney A. Brooks, "Planning Collision Free Motions for Pick and Place Operations"; to appear *International Journal of Robotics Research*, vol 2, no. 4, Dec. 1983.

Refereed Conference Papers:

1. Rodney A. Brooks, Russell Greiner and Thomas O. Binford, "The ACRONYM Model-Based Vision System"; *Proceedings IJCAI 6*, Tokyo, August 1979, 105-113.

2. Rodney A. Brooks and Thomas O. Binford, "Interpretive Vision and Restriction Graphs"; *Proceedings of the First Annual National Conference on Artificial Intelligence*, sponsored by AAAI, Stanford, August 1980, 21-27.

3. Thomas O. Binford, Rodney A. Brooks and David Lowe, "Image Understanding via Geometric Models"; *Proceedings of the Fifth International Conference on Pattern Recognition*, Miami, December 1980, 364-369.

4. Rodney A. Brooks, "Model-Based Three Dimensional Interpretations of Two Dimensional Images"; *Proceedings IJCAI-7*, Vancouver, Canada, August 1981, 619-624. (This is an earlier version of the IEEE PAMI paper above.)

5. Rodney A. Brooks, Richard P. Gabriel and Guy L. Steele Jr., "An Optimizing Compiler for Lexically Scoped Lisp"; *Proceedings ACM Sigplan 1982 Symposium on Compiler Construction*, Boston, June 1982, 261-275.

6. Rodney A. Brooks, Richard P. Gabriel and Guy L. Steele Jr., "S-1 Common Lisp Implementation"; *Proceedings 1982 ACM Symposium on Lisp and Functional Programming*, Pittsburgh, Aug. 1982, 108-113.

7. Rodney A. Brooks, "Solving the Find-Path Problem by Good Representation of Free Space"; *Proceedings of the Second Annual National Conference on Artificial Intelligence*, sponsored by AAAI, Pittsburgh, Aug. 1982, 381-386. (This is an earlier version of the IEEE SMC paper above.)

8. Rodney A. Brooks and Tomás Lozano-Pérez, "A Subdivision Algorithm in Configuration Space for Findpath with Rotation"; *Proceedings IJCAI-8*, Karlsruhe, Germany, August 1983.

9. Rodney A. Brooks, Richard P. Gabriel and Guy L. Steele Jr., "Lisp in Lisp: High Performance and Portability"; *Proceedings IJCAI-8*, Karlsruhe, Germany, August 1983.

10. Rodney A. Brooks, "Find-Path for a Puma-Class Robot"; *Proceedings of the Third Annual National Conference on Artificial Intelligence*, sponsored by AAAI, Washington, D.C., Aug. 1983.

Unrefereed Publications and Internal Reports:

1. Rodney A. Brooks, Russell Greiner and Thomas O. Binford, "A Model-Based Vision System"; *Proc ARPA Image Understanding Workshop*, Cambridge, May 1978, 36-44.

2. Rodney A. Brooks, Russell Greiner and Thomas O. Binford, "Progress Report on a Model-Based Vision System"; *Proc ARPA Image Understanding Workshop*, Pittsburgh, Nov 1978, 145-151. Reprinted in proceedings of an NSF Workshop on the Representation of Three-Dimensional Objects, University of Pennsylvania, May 1979, Section C.

3. Rodney A. Brooks, "Goal-Directed Edge Linking and Ribbon Finding"; *Proc ARPA Image Understanding Workshop*, Menlo Park, Apr 1979, 72-76.

4. Thomas O. Binford and Rodney A. Brooks, "Geometric Reasoning in ACRONYM"; *Proc ARPA Image Understanding Workshop*, Menlo Park, Apr 1979, 48-54.

5. Rodney A. Brooks and Thomas O. Binford, "Representing and Reasoning About Partially Specified Scenes"; *Proc ARPA Image Understanding Workshop*, College Park, Apr 1980, 95-103.

6. Rodney A. Brooks and Thomas O. Binford, "Geometric Modeling in Vision for Manufacturing"; *Proc SPIE*, Washington, Apr 1981.

7. Rodney A. Brooks, "Model-Based 3-D Interpretations of 2-D Images"; *Proc ARPA Image Understanding Workshop*, Washington, Apr 1981, 136-143. (This is an earlier version of the IJCAI 7 paper above.)

8. Rodney A. Brooks, "Symbolic Reasoning Among 3-D Models and 2-D Images"; *Stanford Artificial Intelligence Laboratory*, AIM-343, Ph. D. thesis, June 1981.

9. Rodney A. Brooks, "Solving the Find Path Problem by Representing Free Space as Generalized Cones"; *Massachusetts Institute of Technology Artificial Intelligence Laboratory*, AIM-674, May 1982 (later appeared in IEEE-SMC).

10. Rodney A. Brooks, "Representing Possible Realities for Vision and Manipulation"; *IEEE Pattern Recognition and Image Processing Conference*, Las Vegas, June 1982, 587-592. (Invited Paper)

11. Rodney A. Brooks, "Symbolic Error Analysis and Robot Planning"; *Massachusetts Institute of Technology Artificial Intelligence Laboratory*, AIM-685, Sept. 1982 (later appeared in Robotics Research).

12. Rodney A. Brooks and Tomás Lozano Pérez, "A Subdivision Algorithm in Configuration Space for Findpath with Rotation"; *Massachusetts Institute of Technology Artificial Intelligence Laboratory*, AIM-684, Dec. 1982.

13. Rodney A. Brooks, "Planning Collision Free Motions for Pick and Place Operations"; *Massachusetts Institute of Technology Artificial Intelligence Laboratory*, AIM-725, May 1983.

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ACADEMIC BACKGROUND

B.S. in Electrical Engineering (1955), Carnegie Mellon University
M.S. in Electrical Engineering (1956), Carnegie Mellon University
Ph.D. in Electrical Engineering (1958), Carnegie Mellon University

PROFESSIONAL EXPERIENCE:

Professor of Electrical Engineering, Stanford University, 1970-present
Director, Stanford Electronics Laboratories, Stanford University, 1972-present
Director, Center for Integrated Systems, Stanford University, 1981-present
Co-Founder and Member of Board, Telesensory Systems, Inc., 1971-present
Director, Integrated Circuits Laboratory, Stanford University, 1969-present
Associate Professor of Electrical Engineering, Stanford University, 1967-70
Director, Integrated Electronics Div., U.S. Army Electronics Lab., 1965-67
Chief, Semiconductor & Microelectronics Branch, U.S. Army Electronics Lab., 1962-65
Head, Microelectronics Section, U.S. Army Electronics Lab., 1959-62
Lecturer, Electrical Engineering Dept., Monmouth College, NJ, 1960-67
Engineer, Westinghouse Electric Corp., Pittsburgh, PA, 1958-59 (+ summers 1955,56)
Engineer, Autonetics, Downey, CA, summer 1957

AREAS OF SPECIALIZATION:

Integrated Electronics, Micropower Electronics, Medical Electronics, VLSI Systems

PROFESSIONAL ASSOCIATIONS:

Fellow, The Institute of Electrical and Electronics Engineers, Inc.
Fellow, American Association for the Advancement of Science
Editor, IEEE Journal of Solid-State Circuits, 1966-71
A.S. Flemming Award, 1967, one of 10 outstanding young scientists in Government
Chairman, 1969 International Solid-State Circuits Conference
Chairman, IEEE Solid-State Circuits Council, 1972
Chairman, 28th Annual Conference on Engineering in Medicine and Biology, 1975
Outstanding Paper Awards, International Solid-State Circuits Conferences 1970, 1975, 1976, 1977, 1978
J.J. Ebers Award, IEEE Electron Devices Society, 1980

Member: The Electrochemical Society, Biomedical Engineering Society, American Association of University Professors, National Academy of Engineering, Tau Beta Pi, Eta Kappa Nu, Sigma Xi, Phi Kappa Phi

PUBLICATIONS: Book - Micropower Circuits, J. Wiley & Sons, 1969
Technical Articles - 250 +

PATENTS: 6

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RECENT PUBLICATIONS

R.D. Davies and J.D. Meindl, "Considerations for High-Speed and Analog-Circuit-Compatible I^2L and the Analysis of Poly I^2L," IEEE J. Solid-State Circuits, SC-14(5):876-886, October 1979.

K.C. Saraswat, F. Mohammadi and J.D. Meindl, "WSi_2 Gate MOS Devices," IEEE International Electron Devices Meeting, Washington, December 1979, IEDM Technical Digest, pp. 462-464.

Levy Gerzberg and James D. Meindl, "Optimization, Performance and Limitations of Monolithic Polycrystalline Silicon Distributed RC Devices," IEEE International Electron Devices Meeting, Washington, December 1979, IEDM Technical Digest, pp. 502-505.

F. Mohammadi, K.C. Saraswat and J.D. Meindl, "A High Voltage MOSFET in Polycrystalline Silicon," IEEE Trans. on Electron Devices, ED-27(1): 293-298, Jan. 1980.

K.N. Ratnakumar, J.D. Meindl and D.J. Bartelink, "Performance Limits of E/D NMOS VLSI," IEEE International Solid-State Circuits Conference, Digest of Technical Papers, February 1980, pp. 72-73 & 260.

C.S. Sander, J.W. Knutti and J.D. Meindl, "A Monolithic Capacitive Pressure Sensor with Pulse-Period Output," IEEE International Solid-State Circuits Conference, Digest of Technical Papers, February 1980, pp. 78-79.

T.R. Harrison, J.W. Knutti, H.V. Allen and J.D. Meindl, "Micropower Linear Compatible I^2L Techniques in Biomedical Telemetry," IEEE International Solid-State Circuits Conference, Digest of Technical Papers, February 1980, pp. 214-215.

N.C.C. Lu, L. Gerzberg and J.D. Meindl, "A Quantitative Model of The Effect of Grain Size on the Resistivity of Polycrystalline Silicon Resistors," IEEE Electron Device Letters, EDL-1(3):38-41, March 1980.

C.S. Sander, J.W. Knutti and J.D. Meindl, "A Monolithic Capacitive Pressure Sensor with Pulse-Period Output," IEEE Trans. on Electron Devices, ED-27(5):927-930, May 1980.

J.W. Knutti, H.V. Allen and J.D. Meindl, "Implantable Ultrasonic Telemetry System Architectures, Assembly and Applications," in Biotelemetry V, G. Matsumoto and H.P. Kimmich, eds., Nijmegen, Sapporo, 1980, pp. 55-58.

H.V. Allen, J.W. Knutti and J.D. Meindl, "A General Purpose Six Channel Implantable Telemetry System," in Biotelemetry V, G. Matsumoto and H.P. Kimmich, eds., Nijmegen, Sapporo, 1980, pp. 50-53.

L. Gerzberg and J.D. Meindl, "Power-Spectrum Centroid Detection for Doppler Systems Applications," Ultrasonic Imaging, 2(3):232-261, July 1980.

L. Gerzberg and J.D. Meindl, "The $\sqrt{f}$ Power-Spectrum Centroid Detector: System Considerations, Implementation, and Performance," Ultrasonic Imaging, 2(3):262-289, July 1980.

E. Wildi, J.W. Knutti, H.V. Allen and J.D. Meindl, "Dynamics and Limitations of Blood/Muscle Interface Detection Using Doppler Power Returns," IEEE Trans. on Biomedical Engineering, BME-27(1):565-573, October 1980.

J.D. Meindl, "Biomedical Implantable Microelectronics," Science, 210:263-267, 17 October 1980.

A.L. Susal, J.T. Walker and J.D. Meindl, "Small-Organ Dynamic Imaging System," J. Clin. Ultrasound, 8:421-426, October 1980.

L. Gerzberg, N.C.C. Lu and J.D. Meindl, "Scaling and Limits of Monolithic Polycrystalline Silicon Resistors," 38th Annual Device Research Conference, Ithaca, NY (Abstract in IEEE Trans. on Electron Devices, ED-27(11):2184, Nov. 1980).

J.W. Knutti, H.V. Allen and J.D. Meindl, "Integrated Circuit Implantable Systems," ISA Transactions, 19(4):47-53, 1980.

E. Wildi, J.W. Knutti and J.D. Meindl, "A Micropower, Small Input-to-Output Delay, High-Voltage Bipolar Driver/Demultiplexer IC," IEEE J. Solid-State Circuits, SC-16(1):23-30, February 1981.

J.D. Meindl, K.N. Ratnakumar, L. Gerzberg and K.C. Saraswat, "Circuit Scaling Limits for Ultra Large Scale Integration," IEEE International Solid-State Circuits Conference, Digest of Technical Papers, Feb. 1981, pp. 36-37.

L. Gerzberg, N.C.C. Lu and J.D. Meindl, "A Monolithic Power-Spectrum Centroid Detector," IEEE International Solid-State Circuits Conference, Digest of Technical Papers, February 1981, pp. 164-165.

N.C.C. Lu, L. Gerzberg, C.Y. Lu and J.D. Meindl, "A New Conduction Model for Polycrystalline Silicon Films," IEEE Electron Device Letters, EDL-2(4):95-98, April 1981.

N.C.C. Lu, L. Gerzberg, C.Y. Lu and J.D. Meindl, "Modeling and Optimization of Monolithic Polycrystalline Silicon Resistors," IEEE Trans. on Electron Devices, ED-28(7):818-830, July 1981.

R.B. Lefferts, R.M. Swanson and J.D. Meindl, "The Effect of Metallic Precipitates on the I-V Characteristics of Bipolar Transistors and Diodes," Device Research Conference, Santa Barbara, June 1981 (abstract).

K.N. Ratnakumar, J.D. Meindl and D.L. Scharfetter, "New IGFET Short-Channel Threshold Voltage Model," Technical Digest, International Electron Devices Meeting, 1981, pp. 204-206.

D. Harame, J. Shott, J. Plummer and J. Meindl, "An Implantable Ion Sensor Transducer," Technical Digest, International Electron Devices Meeting, 1981, pp. 467-470.

L. Gerzberg, N.C.C. Lu and J.D. Meindl, "Polycrystalline Silicon Resistors: Theory, Technology, Applications and Limitations," Proc. Materials Research Society Annual Meeting, Boston, November 1981.

H.J. Singh, N.C.C. Lu, D.J. Bartelink, L. Gerzberg and J.D. Meindl, "Characterization of Electrical Conduction in Laser-Recrystallized Polycrystalline Silicon Resistors," Proc. Materials Research Society Annual Meeting, Boston, November 1981.

J.D. Meindl, "Microelectronics and Computers in Medicine," Science, 215:792-797, 12 February 1982.

R.B. Lefferts, R.M. Swanson and J.D. Meindl, "A Recombination Model for the Low Current Performance of Submicron Devices," IEEE International Solid-State Circuits Conference, Digest of Technical Papers, Feb. 1982, pp. 16-17, 281.

J.D. Meindl, "Implantable Instrumentation," in Electronics Engineers' Handbook, 2nd ed., D.G. Fink and D. Christiansen, eds., McGraw-Hill, 1982, pp. 26-43 - 26-51.

N.C.C. Lu, Levy Gerzberg and J.D. Meindl, "Scaling Limitations of Monolithic Polycrystalline-Silicon Resistors in VLSI Static RAM's and Logic," IEEE Trans. on Electron Devices, ED-29(4):682-690, April 1982.

K.N. Ratnakumar and J.D. Meindl, "Short-Channel MOST Threshold Voltage Model," IEEE J. Solid-State Circuits, SC-17(5):937-948, October 1982.

N.C.C. Lu, L. Gerzberg, C.Y. Lu and J.D. Meindl, "A Conduction Model for Semiconductor-Grain-Boundary, Semiconductor Barriers in Polycrystalline-Silicon Films," IEEE Trans. on Electron Devices, ED-30(2):137-149, February 1983.

J. Pfiester, J.D. Shott and J.D. Meind., "E/D CMOS - A High Speed VLSI Technology," Proc. 1983 Symposium on VLSI Technology, Maui, Hawaii, September 1983.

J. D. Meindl, "Theoretical, Practical and Analogical Limits in ULSI," Technical Digest, International Electron Devices Meeting, 1983, December 1983.

H.J. Singh, K.C. Saraswat, J.D. Shott, J.P. McVittie and J.D. Meindl, "Scaling of SOI/PMOS Transistors," Technical Digest, International Electron Devices Meeting, 1983, December 1983.

L.L. Lewyn and J.D. Meindl, "An IGFET Inversion Charge Model for VLSI Systems," Technical Digest, International Electron Devices Meeting, 1983, December 1983.

Unpublished Presentations, Panel Participation, Meeting Chairmanships 1982-83

"ULSI and Beyond," talk at Dedication Ceremony of Xerox Large Area Electronics Facility, Rochester, NY, April 6, 1982.

"Integrated Systems," lecture series in Stanford Engineering Executive Program, June 27-July 9, 1982.

Chairman, 7th International Symposium on Biotelemetry, August 16-20, 1982, Stanford University.

"Projections of VLSI Technology Trends," talk at DoD-AOC Electronic Warfare Technical Symposium, San Francisco, October 11-14, 1982.

Panelist, "The Silicon Foundry-Myth or Reality?" IEEE International Electron Devices Meeting, Washington, D.C., December 14, 1982.

Panelist, "Joint R and D - Current and Future Plans," IEEE International Solid-State Circuits Conference, New York, February 23-25, 1983.

Panel Moderator, "Practical versus Theoretical Limits of VLSI," IEEE International Solid-State Circuits Conference, New York, February 23-25, 1983.

"The Future of VLSI," talk in NBS Colloquium Series, National Bureau of Standards, Gaithersburg, Maryland, March 11, 1983.

Keynote Address in one-day symposium: "Processing and Devices: Recent Advances," IEEE Electron Devices Group, Stanford University, April 30, 1983.

"Center for Integrated Systems," talk in Development Office Seminar, Stanford University, April 22, 1983.

Session Chairman, "University Microelectronics Fabrication/Instructional Programs - I," at University/Government/Industry Microelectronics Symposium, College Station, Texas, May 25-27, 1983.

"Joint University-Industry R&D," talk at University/Government/Industry Microelectronics Symposium, College Station, Texas, May 25-27, 1983.

Panel Moderator, "Joint Research and Development Efforts," at University/Government/Industry Microelectronics Symposium, College Station, Texas, May 25-27, 1983.

"Physical Limits in VLSI," talk at 4th Whitney Symposium on Science & Technology, General Electric C., Schenectady, NY, June 7-10, 1983.

"Integrated Systems," lecture series in Stanford Executive Engineering Program, June 20-July 1, 1983.

"The University Role in Semiconductor Research," talk at Semiconductor Industry Service Conference, Palm Springs, California, October 16-19, 1983.

"Ultra Large Scale Integration," talk in Technical Session: Cutting Edge Technologies, at National Academy of Engineering Annual Meeting, Washington, D.C., November 3, 1983.

"Joint Ventures in Research - A University Perspective," talk at Fall Meeting of Industrial Research Institute, Inc., San Francisco, November 6-9, 1983.

DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS
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Curriculum Vitae

Daniel B. DeBra, Professor
Aeronautics and Astronautics, and
Mechanical Engineering;
Director, Guidance and Control Laboratory
(1970 to Present)

Education

B.E.	Mechanical Engineering	Yale	1952
M.S.	Mechanical Engineering	M.I.T.	1953
Ph.D.	Engineering Mechanics	Stanford	1962

Experience

1953-54 The Thermix Corporation, Project Engineer: Design and sales of industrial and power station boiler auxiliary equipment

1954-56 U. S. Air Force, Rome Air Development Center, Mechanical Engineer: Mechanical design of electronic equipment

1956-64 Lockheed Missile and Space Company, Supervisor, Dynamics and Control Analysis, Guidance and Control Department, Satellite Systems: Analysis and design of attitude control and guidance systems for the Agena Satellite

1964-70 Stanford University, Satellite Projects Manager, and Lecturer: Vehicle control systems and sensors

1964-65 Systems Corporation of America, Consultant: Spacecraft attitude control

1965-67 The Jet Propulsion Laboratory, Co-Investigator: Accelerometer applications

1965-69 Stanford Research Institute, Consultant: High-g inertial instrument testing, and applications for inertial instruments

1965-68 Vidya, Division of Itek, Consultant: Guidance and control

1966-68 Chrysler Space Division, Consultant: Precision attitude control

1966-69 RCA-Astro Electronics Division, Consultant: Attitude control of the Stabilite.

Daniel B. DeBra
Resumé (Cont)

Experience (Current Consulting)

1968- Lockheed Missiles & Space Co., Sunnyvale, Calif.;

1968-69 UTC (United Technology Corp.), Sunnyvale, Calif.;

1969 Lockheed-Calif. Co., Burbank, Calif.

1969- Sunstrand Data Control, Redmond, Washington; flight control systems and accelerometer design.

1969-71 Electro Optical Systems, platform design.

1970-72 Cotchett Law Office, and Bronson, Bronson, and McKinnon Law Firm, expert witness on safety rope applications.

1970-74 Nielsen Engineering & Research, Inc., Mountain View, Cal.

1970- Jet Propulsion Lab., Pasadena, Calif; gradiometers

1971- Systems Control Inc., Palo Alto, Calif.

1971- Hughes Research Labs., Malibu, Calif., gradiometer design

1972-75 Redstone Arsenal, Alabama; missile autopilot.

1978- Ford Aerospace, Palo Alto, CA

1978- Martin Marietta, Denver, Colorado

1979- Northrop Corp, Hawthorne, CA

1979- Lawrence Livermore Lab., Livermore, CA. Consultant and summer employee in development of 3rd generation diamond turning machines and related ultra precision machining and technology.

Distinguished Awards

1. "Industrial Research Award 100" for successful flight of drag-free satellite in 1973.
2. Life Member, U.S. National Academy of Engineering, 1981.

Committees - National

1968-74 National Academy of Sciences - Mine Advisory Committee
1970-76 NASA's Research & Technology Advisory Council, Space Vehicles Com.
1968- Society of Automotive Engineers, Aerospace Control and Guidance Systems Committee (ACGSC)
1971- U.S.A.F. Scientific Advisory Board, Guidance & Control Panel
1971-74 U.S.A.F. Joint Working Group on Density Forecasting
1970-75 Engineers' Council for Professional Development, Inc., Student Development Committee
1976- NAS Committee on Geodesy; Chairman, GPS Panel; Committee on Large Space Systems.
1980- DOD Committee member, Defense Science Board, Aircraft
1980- USAF SAB, Division Advisory Group (DAG)

Societies

American Astronautical Society;
American Geophysical Union;
American Institute of Aeronautics & Astronautics
American Society of Engineering Education
American Society of Mechanical Engineers
Institute of Electrical & Electronics Engineers
Institute of Navigation;
Society of Automotive Engineers;
Society of Manufacturing Engineers (Member No. 1542224)

Technical Publications

1. "Gyroscopically Effected Precession in Overhung Rotors at Critical Speeds," M.I.T. Master's Thesis with Chaovana Na Sylvanta, June 1953

2. "Problems of Attitude Control of Satellite and Interplanetary Vehicles." with E. V. Stearns, Electrical Engineer, Vol. 77, No. 12, pp. 1088-1090, December 1958

3. "The Effect of Aerodynamic Forces on Satellite Attitude," J. Amer. Astro. Soc., Vol. 6, No. 3, Autumn 1959

4. "The Effect of Guidance Errors on Astroballistic Trajectories," presented at IRE, PGMIL Third National Convention, Washington, D. C., July 1, 1959

5. "Orbital Plane-Change Maneuver," Astro. Sci. Rev., October-December 1959

6. "Circularization of Elliptic Orbits," with H. B. Gundell, Advances in the Astro. Sci., Vol. 6, January 1960

7. "Ascent Error Analysis and Correction Maneuvers for Circular Orbits," LMSD 446130, February 22, 1960

8. "Two Maneuver Ascents to Circular Orbits," with J. F. Wolfe, J. Astro. Sci., Vol. VII, No. 2, Summer 1960

9. "Rigid Body Attitude Stability and Natural Frequencies in a Circular Orbit," with R. H. Delp, J. Astro. Sci., Vol. III, No. 1 Spring 1961

10. "Vectors and Dyadics: The Natural Tools of Space-Vehicle Mechanics," Advances in the Astro. Sci., Vol. 9, August 1961

11. "Momentum Vector Considerations in Wheel-Jet Satellite Control System Design," with R. H. Cannon, Jr., Progress in Astronautics and Rocketry: Guidance and Control, Vol 8, August 1961, pp. 565-597

12. "The Large Atttitude Motions and Stability, Due to Gravity, of a Satellite With Passive Damping in an Orbit of Arbitrary Eccentricity About an Oblate Body," Ph.D. Thesis, Department of Aeronautics and Astronautics, Stanford University, Stanford, Calif., May 1962

13. "Attitude Stability and Motions of Passive, Gravity-Oriented Satellites," AAS 8th Annual Nat'l Meeting, Washington D.C. 1962

14. "Orbits and Trajectories: Their Mechanics and Control," Chapt. 4 of Astronautics for Science Teachers, edited by John G. Meitner, John Wiley & Sons, Inc. 1965

15. "Principles and Developments in Passive Attitude Control," presented at the Amer. Astronautical Society Meeting, Berkeley, California, 29 December 1965

16. "A Precision, Active, Table-Leveling System," with James C. Mathiesen and Richard Van Patten, presented at the 1966 Guidance and Control Specialist Conference, AIAA, Seattle, Washington, August 15-17, 1966. JSR, vol. 5, no. 9, Sept 1968, pp. 1040-1045.

17. "A Method for Obtaining the Radius of Mars," with A.A. Loomis and R.D. Bourke (of JPL); JGR, vol. 72, no. 4, 15 Feb 1967.

18. "Orbital Gyrocompassing Heading Reference," with J.L. Bowers, J.J. Rodden, and E.D. Scott (all of Lockheed); Journal of Spacecraft and Rockets, vol. 5, no. 8, Aug. 1968.

19. "Flotation Technique Testing of Low-Level Accelerometers," with Barry K. Likeness, paper presented at Fourth Inertial Guidance Test Symposium, Holloman Air Force Base, New Mexico, 6-8 Nov. 1968.

20. "A Comparison of Satellite Drag Measurement Techniques," paper presented at the IInd International Conference on Space Engineering, 7 to 10 May, 1969, Venice Italy.

21. "Attitude-Translation Coupling in Drag-Free Satellites," IIIrd IFAC Conference, Automatic Control in Space, 2 to 6 March 1970, Toulouse, France, with A.W. Fleming and M. Crespo di Silva.

22. "The Stability of Gravity Stabilized Drag-Free Satellites," AIAA J., vol. 9, no. 10, pp. 1980- 1971, with Alan W. Fleming (AIAA 1970 G&C Conf, Aug 1970).

23. "Propulsion Requirements for Drag-Free Satellite," 8th National Electric Propulsion Conference, AIAA, Aug. 31 to Sept 2, 197[illegible], at Stanford University, Stanford, Calif. (to be publ in AI[illegible]

24. "Drag-Free Satellite Control System Technology," Confere[illegible] Experimental Tests of Gravitation Theories, sponsored [illegible] and The European Space Research Organization, held at [illegible] Institute of Technology & JPL, Nov 11-13, 1970.

25. "Estimation in Satellite Control," Ninth Int'l [illegible] Technology & Science, Tokyo, Japan, May 17-[illegible]

26. "A Reduced State Estimator For Orbital [illegible] M.G. Lyons, AIAA Guidance & Control, [illegible] Aug 16-18, 1971, Hempstead, L.I., N[illegible]

27. "A Proposed Lunar Orbiting Gravity Gradiometer Experiment," with J.C. Harrison and P.M. Muller, The Moon, D. Reidel Publishing Co., Dordrecht-Holland, to be published in the Spring of 1972.

28. "Active Control and Gyroscopic Sensing," lectures given at International Center for Mechanical Sciences, Udine, Italy, as part of GYRODYNAMICAL APPLICATIONS TO SPACECRAFT, Sept. 1972. To be published as a monograph.

29. "Flotation Measurement of Accelerometer Errors Below One Micro-g," paper presented at the Sixth Biennial Guidance Test Symposium, Holloman AFB, New Mexico, 88330, Oct 1972, with Don Johansen.

30. "Measurement of Accelerometer Errors Below One Micro-g," paper to be presented at IFAC's Automatic Control in Space Symposium, Genoa, Italy, June 1973, with Don Johansen.

31. "Precise Attitude Control of the Stanford Relativity Satellite," Joint Automatic Control Conf., Ohio State Univ., Columbus, Ohio, Jun 1973, with John Bull.

32. "Precision Pointing Thrustor," AIAA Guidance & Control Conf., Key Biscayne, Fla., Aug. 1973, with John Bull.

33. "A Satellite Free of all But Gravitational Forces: "TRIAD I", Ist International Symposium: The Use of Artificial Satellites For Geodesy and Geodynamics, May 14-21, 1973, Athens, Greece, with the Space Dept. of Johns Hopkins Univ., Applied Physics Lab. (see also No. 43.)

34. "Orbital Simulation of Satellite Accelerations for Drag-Free Control and Low-Level Accelerometers," Revue R.A.I.R.O., with Dave Powell, 1973.

35. "Control Law Synthesis and Sensor Design for Active Flutter Suppression," AIAA Guidance & Control Conf., Key Biscayne, Fla., 1973 Sept., with Lyons, Vepa, & McIntosh.

36. "Satellite Attitude Control Simulations," paper presented at the International Seminar Simulation and Space conference, Toulouse, France, Sept. 1973, with Dave Powell.

37. "DISCOS Description," with R.A. Van Patten and R. Hacker, submitted to Applied Physics Lab. of JHU by the Guidance & Control Laboratory, Stanford University.

38. "Disturbance Compensation System Design," APL Technical Digest, Jun. 1973.

Daniel B. DeBra
Resume (Cont)

39. "Nonlinear Identification in the DISCOS Position Sensor," with Pierre Yansouni, AIAA Mechanics & Control of Flight Conf., Anaheim, Calif., Aug 1974.

40. "Minimum Cost Autopilots for Light Aircraft," with A.E. Bryson, Jr., VI IFAC Symposium on Automatic Control in Space, Tsakhkadzor, Armenian SSR, USSR, Aug 26-31, 1974.

41. "Aeronomy Experiments with a Drag-Free Satellite," 6th Conf. on Aerospace & Aeronautical Meteorology, El Paso, Texas, Nov 1974.

42. Space Dept of the Johns Hopkins University Applied Physics Lab., and the Guidance & Control Lab. of Stanford University, "A Satellite Freed of all but Gravitational Forces: 'TRIAD I'," J. Spacecraft, vol. 11, no. 9, Sept. 1974, pp. 637-644.

43. "Attitude Translational Coupling in a Rotating Drag-Free Satellite," with S. Sanz, AAS/AIAA Astrodynamics Specialist Conf., Nassau, Bahamas, Jul 28-30, 1975, Paper No. AAS 75-026.

44. "Attitude Estimation of a Rotating Satellite with Measurement of the Angular Acceleration," with S. Sanz, AIAA Guidance & Control Conf. Boston, Mass Aug. 20-22, 1975, Paper No. 75-1105.

45. "Exospheric Density Measurement from the Drag-Free Satellite, TRIAD," with K. Moe, M. Moe, R. Van Patten, and M. Ruggera, JGR, 1976.

46. "Mass Center Estimation of a Drag-Free Satellite," with S. Sanz, 1975 Int'l Fed. of Automatic Control (IFAC), Boston, Mass, Aug 1975.

47. "Estimation of Gyro Parameters for Experimentally Developed Gyro Models," with Vance Coffman, AIAA Guidance & Control Conf., Boston, Mass, Aug. 20-22, 1975.

48. "Caging Mechanism for a Drag-Free Satellite," with R. Hacker, and J. Mathiesen, Aerospace Mechanism Symposium, JPL, Apr 1976.

49. "Control Requirements of Space Relativity Experiments," invited paper for VIIth IFAC Sym., "Automatic Control in Space," Rottach-Egern, Germany, May 17-21, 1976.

50. "Orbital Coupling for Proof Mass Control in a Partially Drag-Free Satellite," with C. Ray, VIIth IFAC Sym., "Automatic Control in Space," Rottach-Egern, Germany, May 17-21, 1976.

51. "Complex Symmetric Root Square Locus With an Application to a Spinning Drag-Free Satellite," with M.G. Tashker, VIIth IFAC Sym., Rottach-Egern, Germany, May 17-21, 1976.

Daniel B. DeBra
Resumé (Cont)

52. "A New Control System Design Course," with M.G. Tashker, IFAC Symposium, Barcelona, Italy, Mar, 1977.

53. "The Effects of Relative Instrument Orientation Upon Gravity Gradiometer System Performance," with E.J. Pelka, AIAA J. of Guidance & Control, Vol. 2, No. 1, Jan-Feb 1979, pp. 18-24.

54. "Control Technology Challenges for Gravitational Physics Experiments in Space," J. of Guidance and Control (AIAA), Mar-Apr 1979.

55. "The Impact of Technology on Geodesy," from Impact of Technology on Geophysics, National Academy of Sciences, (Newell, H.E. Editor), Washington, D.C., pp. 22-30, 1979.

56. "Engineering Aspects of the Stanford Relativity Gyro Experiment", (with C.W.F. Everitt and R.A. Van Patten), paper presented at the AAS Conference, Jan. 1981.

57. "Evolving Spacecraft Control," (Plenary Session Address), IFAC Conference, Kyoto, Japan, Aug 1981. (Published in IFAC Proc.)

58. "Damping Vibration for Special Lathe", American Machinist, Aug. 1981.

59. DeBra, D.B., and Warner, R.E., "Pneumatic Isolation Systems With Linear Passive Damping", Lawrence Livermore National Lab., UCRL No. 53209, Jan. 19, 1982, Livermore, CA 94550

60. "Elastic Suspension of a Wing Tunnel Test Section", (with R. Hacker), paper presented at the 16th Aerospace Mechanisms Sym., J. F. Kennedy Space Center, May 1982.

61. "Attitude and Translation Control of a Low-Attitude GRAVSAT", (with C. Ray, R.E. Jenkins, R.A. Van Patten and J.L. Junkins), AIAA/AAS Astrodynamics Conf., Aug. 9-11, 1982, San Diego, CA

62. "Gravity Probe B — New Control System Technology in Space," (with Francis Everitt), AIAA/SPIE/OSA Technology for Space Astrophysics — The Next 30 Years, Danbury, Connecticut, October 4-6, 1982.

Daniel B. DeBra
Resume (Cont)

American Institute of Aeronautics and Astronautics (AIAA) Activities

Year	Division	Position
1961	National	Administrative Chairman for the 1961 Guidance and Control Conference.
1961	S.F. Section	Recipient of the Outstanding Service Award for the American Rocket Society.
1962	S.F. Section	Treasurer (Peninsula Section of the American Rocket Society).
1963, 64,	S.F. Section	Vice Chairman; Chairman
1964, 65, 66	National	Guidance & Control Technical Committee
1965, 66, 67	S.F. Section	Advisory Board; Director, Nominations Committee
1966 to Date	National	Education and Student Affairs Committee
1966	National	Chairman, 1966 Guidance & Control Technical Conference
1966	Region VI	Chairman, Judges Committee for Region VI Student Conference
1967 to 1969	National	Chairman, Younger Member Affairs Committee
1967 to 1969	National	Special Deputy on Student Affairs to AIAA Vice President-Section Affairs
1967 to 1970	National	Membership Committee
1969 to	National	ECPD (evaluate university curricula)
1970 to	National	Member, Education Committee
1971 to 1972	National	1972 JACC Chairman, for Joint Automatic Control Conf., Aug. 1972; member of the JACC Steering Committee; Vice Chairman of AACC Space Committee.
1973 to 1975	National	Vice President, Education

Registration

Professional Electrical Engineer, State of California (No. EE 6846)

Listings

American Men of Science; Leaders in American Science; Who's Who in the West.

GORDON S. KINO

[redacted]

Education:	BSc. London University, England, 1948 (Mathematics). MSc. London University, England, 1950 (Mathematics). Ph.D. Stanford University, Ca., 1955 (Electrical Engineering).
Employment:	Jr. Scientist, Mullard Radio Valve Co., England, 1947-1951. Research Associate, Electronics Res. Labs., Stanford University, Ca., 1951-1955. Member, Technical Staff, Bell Telephone Labs., Murray Hill, New Jersey, 1955-57. Research Associate, Stanford University, Ca., 1957-61. Associate Professor, Stanford University, Ca., 1961-1965. Visiting Professor, University College, London, England, 1967-1968. Professor, Electrical Engineering, Stanford University, 1965- Professor-by-Courtesy, Applied Physics, Stanford University, 1976-
Honors:	Guggenheim Fellow, 1967-1968 Fellow, American Physical Society Fellow, IEEE Member, National Academy of Engineering Fellow, AAAS
Fields of Interest:	Microwave triodes, traveling wave tubes, klystrons, microwave tubes, magnetrons, electron guns, gaseous plasma, wave propagation in plasmas, solid state oscillators and amplifiers, microwave acoustics, acoustic imaging devices, nondestructive testing, and fiber optics.
University Committees:	Graduate Admissions Committee, AP Department Committee on Graduate Studies, EE Department
Other:	Chairman, IEEE Ultrasonics Group - Fellow Committee Member, Materials Research Council - DARPA Member, ADCOM Ultrasonics Group - IEEE Member, IEEE External Awards Committee
Invited Talks:	Australia, England, Finland, France, Italy, Japan, and in the United States.
Author:	"Space Charge Flow," Kirstein, P. T., Kino, G. S., and Water, W. E., McGraw-Hill, New York, 509 p., 1967.
Publications:	ca. 300 papers.

5-20-82

BIOGRAPHY

GENE F. FRANKLIN, Professor of Electrical Engineering
Stanford University

Digital Control,
Computer-Aided Design Techniques

B. S., Georgia Institute of Technology

M. Sc., MIT

Ph.D., Columbia University

On Stanford faculty since 1957

Research interests: dynamic system identification for control, model simplification for minimal order dynamics, implementing adaptive digital control based on the development of electronic microprocessors and microcomputers, development of interactive design aids on a computer.

Associate Provost for Computing at Stanford University (1971-1976)

Member of SIAM, Sigma Xi. Fellow of IEEE.

Coauthor (with Ragazzini) of "Sampled Data Control Systems", McGraw-Hill Book Co., and author of 15 technical papers. Coauthor (with J. D. Powell) of, "Digital Control of Dynamic Systems," Addison-Wesley 1980.

INFORMATION SYSTEMS LABORATORY
Department of Electrical Engineering
STANFORD UNIVERSITY Stanford, CA 94305

GENE F. FRANKLIN
Professor of Electrical Engineering
(415) 497-4837

<u>Gene F. Franklin</u> (M' - SM' - F'78)

Gene F. Franklin received the B.E.E. from Georgia Tech in 1970, the M.S.E.E. from M.I.T. in 1952, and D. Eng.Sci. from Columbia in 1955. He was on the faculty of Columbia from 1952 until 1957 and has been at Stanford since 1957. At Stanford he was Associate Provost for Computing from 1971 until 1976.

He was chairman of the 1964 JACC at Stanford, and a member of the Control Society Administration Committee from 1964-1967. He was vice-chairman of the IFAC Theory Committee from 1969 to 1972. He is currently a member of SIAM and IEEE.

His teaching and research interests are in digital control, especially system identification and adaptive control.

LAMBERTUS HESSELINK

PII Redacted Department of Aeronautics/Astronautics
Durand Bldg., Rm. #377
Stanford University
Stanford, California 94305
Phone: 415-497-3466

[redacted]

ACADEMIC HISTORY

Ph.D.	1977	California Institute of Technology Applied Mechanics, minor Physics/Applied Physics Thesis: An Experimental Investigation of Propagation of Weak Shock Waves in a Random Medium
Eng.	1974	Twente Institute of Technology Applied Mechanics (The majority of studies and research leading toward this degree were performed at Caltech.)
M.S.	1972	California Institute of Technology Mechanical Engineering
B.S.	1971	Twente Institute of Technology Applied Physics
B.S.	1970	Twente Institute of Technology Mechanical Engineering

SCHOLARSHIPS AND ACADEMIC HONORS

1970	The Stheeman Prize, Twente Institute of Technology
1966-1971	Dutch Government Fellowship for studies abroad Fullbright Travel Grant
1972-1977	Graduate Research Assistantship
1974-1975	Josephine de Karman Fellowship
1983	Award: Engineer of the year 1982 AIAA Northern California chapter

EMPLOYMENT RECORD

November 1980 - Present	Assistant Professor in Aeronautics and Astronautics department and, by courtesy, in the Electrical Engineering department at Stanford University.
October 1970 - Oct. 1980	Senior Research Fellow in Fluid Mechanics and Instructor in Applied Physics at Caltech. In charge of the graduate course Modern Optics, APh 153 abc.
June 1978 - Sept. 1979	Instructor in Applied Physics in charge of APh 153 abc and Research Fellow in Fluid Mechanics at Caltech.
March 1978 - Oct. 1979	Consultant for Space and Communications Group, Hughes Aircraft Company.
June 1977 - 1978	Research Fellow in Fluid Mechanics Graduate Aeronautical Laboratories California Institute of Technology.

MEMBERSHIPS IN PROFESSIONAL SOCIETIES

Sigma Xi

American Physical Society

Optical Society of America

SPIE, the International Society for Optical Engineering

RESEARCH EXPERIENCE

Fluid Mechanics
- Linear and nonlinear wave propagation
- Turbulent mixing
- Aerodynamic noise

Optics
- Interferometry
- Holography
- Flow visualization
- Speckle
- Fluorescence
- Non linear optics

Low Temperature Physics

Cryogenic shock waves

Second sound holography

Digital and analog image processing

PATENT: U.S. Patent Application, 1977, Laser Interferometer Probe

PUBLICATIONS

1. Flow visualization methods for the analysis of compressible flows. B.S. Thesis, Twente Institute of Technology, 1970 (in Dutch).

2. Calculations and measurements on dielectric resonant cavities for use in E.S.R. experiments. B.S. Thesis, Twente Institute of Technology, 1971 (in Dutch).

3. Noise production by a sonic hot jet (Part I), The propagation of a shock wave through a random medium (Part II), Eng. Thesis, Twente Institute of Technology, 1974 (in Dutch).

4. An experimental investigation of propagation of weak shock waves in random medium, Ph.D. Thesis, California Institute of Technology, 1977.

5. An experimental investigation of the propagation of weak shock waves in a random medium, Proceedings 11th. International Symposium on Shock Tubes and Waves, Seattle, Wa., July 1977.

6. *Modern Optical Methods in Engineering Research.* Notes for workshop conducted at Stanford University, July 26, 1978, California Institute of Technology, 1978.

7. Laser propagation through a turbulent gaseous medium, Meteorological Optics Meeting, Keystone, Colorado, August 28-29, 1978.

8. *Modern Optics,* Lecture Notes, California Institute of Technology, 250 pages, 1979.

9. An experimental investigation of the propagation of weak shock waves through a random medium (with B. Sturtevant). Submitted for publication in the J. Fluid Mech.

10. Propagation of shock waves in random media. Proceedings 12th International Symposium on Shock Tubes and Waves, Jerusalem, Israel, July 1980.

11. Digital image processing of flow visualization photographs (with B. White). Appl. Opt., May 15, 1983.

12. Propagation of shock waves through non-uniform and random media. Proceedings 13th International Symposium on Shock Tubes and Waves, Niagara Falls, NY, July 1981.

13. A holographic schlieren lens for use with strongly refracting objects. In preparation for publication in Applied Optics.

14. Multiple Exposure Holographic Display of C.T. Medical Data (with K.M. Johnson, and J.W. Goodman), Proc. SPIE, 367, p149, 1982

15. Holographic Reciprocity Law Failure, (with K.M. Johnson, and J.W. Goodman), accepted for publication in Applied Optics.
16. Holgraphic display devices, Invited lecture, Proc. SPIE, 402, 1983
17. Quantitative three-dimensional flow visualization, Proc Int. Symp. Flow Vis., Ann Arbor Michigan, 1983
18. Three-dimensional tomographic reconstruction of the flow around a revolving helicopter rotorblade; a numerical simulation, Proc Int. Symp. Flow Vis., Ann Arbor Michigan, 1983

Editor.

Proceedings of the 26 th International SPIE Meet, section on 3-D Processing and Display of Data, August 26-27, 1982, San Diego.

Meetings

Meeting organizer and co-chairman of the 26 th International SPIE meet in San Diego, section on 3-D Processing and Display of Data, August 26-27, 1982, San Diego.

Victor Scheinman
Department of Mechanical Engineering
Stanford University

Professional Positions

1980- Vice President Advanced Systems- Automatix Incorporated
Responsible for new robotics and automation systems research and development.

1977-1979 General Manager- Unimation Inc., West Coast Div.
Founded this division for the purpose of advanced robotics research and development. I proposed, planned and designed the PUMA robot system.

1973-1977 President/Founder- Vicarm Inc.
Founded Vicarm Inc. to manufacture a new generation of computer controlled robots based on extension of work in the field of Artificial Intelligence at Stanford University and MIT. These all electric robots featured computed path control and a high level programming language. To furthur development and expansion I negotiated the sale of the company to Unimation Inc.

1970-1973 Research and Development Engineer- Stanford University
Under ARPA and NSF grants I developed a number of computer controlled robots and robot system components and accessories.

1972- Staff Research Scientist- Mass. Inst. of Technology
As visiting DSR staff member I spent six months designing a new mini-robot for artificial intelligence related uses and applications under an ARPA contract. This robot design was later developed and expanded into the Vicarm robots and more recently the PUMA robot.

1969-1970 Automation Engineering Specialist- Raychem Corporation
Designed and developed mechanical, control and electronic systems for prototype automatic assembly and manufacturing equipment for electrical components.

1965-1969 Research Assistant- Stanford University
I developed several computer controlled robots. These included hydraulic, pneumatic and electrical manipulator systems.

Victor Scheinman - continued

Degrees

1963- Mass. Inst. of Technology- MS Aeronautics and Astronautics
1965- Stanford University- MS Mechanical Engineering- Design.
1967- Von Karman Institute-Belgium- Dipl. Eng.-Fluid Mechanics
1969- Stanford University- Engr.- Mechanical Engineering-Design
1974- Stanford University- PhD candidate- interrupted in 1975.
1981- Stanford University- PhD expected- Automation Engineering.
In 1979 I returned to complete my PhD research on robotic issues in automation. Part of the dissertation research involves development of a prototype of a next generation modular and distributed assembly system.

Academic Honors

1963- MIT Luis De Florez Award for outstanding ingenuity in Engineering.

1966- NATO Fellowship- Study and research work in Fluid Mechanics- Von Karman Institute- Belgium.

1968- Devol Research Company Fellowship- Stanford University Robotics studies and research work.

Papers and Lectures

I have presented a number of papers, mostly in the field of robotics and automation, at national and international conferences. I have given lectures at meetings of organizations such as SME, ASME, ACM, and have also chaired and organized complete sessions at several national conferences. A more complete list of publications is available. I have been recently featured or mentioned in several non-technical national magazines including Fortune (Dec. 17,1979) and Readers Digest (April 1980).

APPENDIX C

INTERACTIONS

The new Center for Automation and Manufacturing Science at Stanford has drawn us together in many ways during this first year, and has begun to attract a number of our talented colleaques to contribute in important ways to manufacturing technology. We have had a steady stream of visitors to our Center from many industries and from the world scientific community in robotics. We have taken part in several key invitational conferences with government research leaders in the field. And we have begun several new joint projects with industrial partners.

Inside Stanford

Within Stanford, the automatic control students of Professors Cannon, DeBra, Bryson, Breakwell, Franklin and Powell are totally intermingled and interactive, as are the computer science students of Professors Binford, Brooks, and McCarthy. Now these two groups of students — about 35 in all — are meeting regularly to probe each other's research directions. With Air Force Center funding the assembly research part of Prof. Binford's laboratory has now moved to the Durand Building, colocated with the manipulator control research of Prof. Cannon's group.

In this same laboratory the new high precision manufacturing project of Professors DeBra, Binford and Hesselink will develop its new machines. (The Laser Optical Processing Laboratory of Professors Hesslink and Goodman is across the hall.)

The fact that Air Force Center funding could be provided to Professor Meindl, Codirector of Stanford's large Center for Integrated Systems, has formed a tie with that pioneering group in VLSI. We have conducted a series of seminars this year on future robot sensors, with Professors Meindl, Hesselink, Cannon, DeBra, and Kino. As described in Part 4 of this Technical Report, Professor Meindl's group is developing a tactile array touch sensor for the fingertips of future hands. Professor Kino's well-known work in acoustic nondestructive testing suggests an excellent basis for developing acoustic proximity sensing for robots, which we hope the Center can initiate in the near future. We anticipate also developing future laser optical sensors of various types for manipulator and assembly tracking, in cooperation with Professor Hesselink's optics team.

With the Research and Air Force Technical Community

Our connections with research groups outside Stanford are many and deep. Many of the leaders in robotics and automation did their doctoral or post-doctoral work at Stanford, including Patrick Winston, Director of the MIT Artificial Intelligence Laboratory, Raj Reddy, Director of the CMV Robotics Center, Victor Scheinman, Vice President, Engineer/Research, of Automatix, Bruce Shimano and Brian Carlisle, co-founders of Adept (formerly Unimation West), and Professors K.D. Wise and S.Genapathy of the University of Michigan's Robotics Center. About 40 others are listed below. In 1981-1982 Professor Binford spent half time at MIT. Victor Scheinman serves as a consultant to our Stanford Center. Particularly invaluable is his engineering counsel at quarterly design reviews. Our

continuing collaboration with SRI robotics and manufacturing research is described below.

We have benifited very much from our participation in five significant invitational technical conferences in this first year:

- The Air Force/DARPA Robotics Workshop in Denver, March 1983.
- The Tri-Service Workshop on Manufacturing at the Xerox International Center in June, 1983.
- The International Symposium of Robotics Research at Bretton Woods, New Hampshire, in August, 1983.
- The DARPA Conference on Mechanical Innovations in Robotics at Menlo Park, California in October, 1983.

These have provided the chance to become familiar in some depth with research throughout the Air Force/DARPA funded community and throughout the world. Equally important, they increased the number of the key people we now know and will be visiting at their laboratories.

With the Manufacturing Industry

This AFOSR project has contributed to making close contacts with several companies, contacts that facilitate technology transfer of the most effective kind: with people in joint efforts.

Professor Binford has participated as a sub-contractor to Honeywell along with Unimation West (now Adept Technology Inc.) and SRI, Intl. in the Intelligent Task Automation program. A strong and active transfer of force sensing and control technology to Honeywell and Unimation West is occurring. Indirect transfer is expected from the strong Stanford-SRI collaboration on model-based vision for the ITA program, using Stanford's ACRONYM system.

We have also collaborated with Unimation West in design and implementation of torque sensors for one joint of the Unimate PUMA 560. This contributes further to transfer of force sensing technology.

A contract has been arranged with IBM which provides Stanford with two IBM robots (RS-1 and 7535) for three years. The project involves close interaction with researchers at IBM, San Jose. The project includes assembly and analysis of assembly. It has already provided input into this program.

We are working out a basis for collaboration with Hewlett Packard. HP has already contributed two computers for our work in manufacturing. Arrangements are being negotiated with Hewlett Packard for a joint effort in automation for semiconductor manufacturing.

Another major enterprise with which we have close collaboration is the General Motors Corporation. As Chairman for the General Motors Science Advisory Committee, Professor Cannon has worked closely with managers of the car divisions and the manufacturing development staff as they address the many forms of automation in their corporate-wide "factory of the future" program.